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Development Of A DC Propulsion System For An Electric Vehicle

FINAL REPORT

W.L. Kelledes
Eaton Corporation
Engineering & Research Center

January, 1984

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-258

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

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1.0 SUMMARY

This report describes the work done and results achieved under DOE/NASA Contract DEN3-258 "Development of a DC Propulsion System for an Electric Vehicle".

The objective of this program was to evaluate the suitability of the Eaton automatically shifted mechanical transaxle concept for use in a near-term dc powered vehicle.

The transaxle was developed from the original two-speed version to a three-speed, more suited to the characteristics of a dc motor. A custom made traction motor and chopper-controller were designed and constructed to complement the transaxle. The system was then installed in a test bed vehicle for performance and efficiency testing at the Eaton Marshall, Michigan test track.

Design information and test results are given both for the individual components and for the complete system.

2.0 INTRODUCTION

Eaton commenced work on EV propulsion system development in 1977 and was awarded a contract in March of 1978 to construct an experimental Phase 1 ac Propulsion System to be bedplate mounted and tested.

Following the successful completion of this contract, contract work on a Phase II ac system for vehicle trials started. This experimental, integrated, ac system, which incorporates technology that are suitable for production in the 1980's, made use of an Eaton automatically shifted highly efficient mechanical transaxle concept specifically developed for EV application.

The objective of the dc Propulsion System Contract, awarded in October 1981, was to evaluate the suitability of the transaxle concept for use with a near-term DC electric powertrain.

The system was to make use of available components where appropriate. It was not to utilize high cost power semiconductors. Components were to be as simple and inexpensive as possible so as to be suitable for introduction by 1986. To this end, the motor and controller were designed and developed by Eaton to complement the characteristics of the transaxle.

3.0 SYSTEM OVERVIEW

In order to produce as simple and inexpensive propulsion system as possible, tradeoffs were made between the major system components to optimize system performance and lower total cost.

To be able to use a lighter, less expensive motor, an additional gear was added to the transaxle. With the high ratio provided in low gear, lower armature currents would give acceptable acceleration. With lower armature current, a single low cost power switching device could be used.

By increasing the transaxle complexity only slightly, significant reductions were made in complexity and cost of the motor and controller.

Using a separately excited motor operating predominately in the weak field condition meant a lower thermal capacity required for the controller and much higher efficiency when in the field weakening mode. Since the motor was to be operated primarily in field control, a method of using the same chopper for armature and field control was devised, further reducing system complexity and cost.

A technical overview of the system follows. Individual component specifications are providing in their own report sections:

1. The propulsion system utilizes a separately excited dc traction motor.

2. The transaxle has three instead of the two-speeds used for the ac propulsion system.

3. The chopper uses a single power switching device.

4. The controller switches the chopper from the armature to the field circuits depending on the motor operating speed.

5. The controller uses a microprocessor to perform the gear shifts and motor/transaxle speed synchronization.

4.0 DESIGN AND ANALYSIS

The propulsion system is designed for a test bed vehicle with a curb weight of 1590 Kg (3500 lbs.) and a maximum payload of 400 lbs. The vehicle used is a two-door hatchback, four-passenger type (Mercury Lynx).

Performance goals for the vehicle are as follows:

1. **Top Speed** - 105 Km/hr (65 mph)
   Paved level road, no wind
2. **Acceleration** - 0-48 Km/hr (0-30 mph) in 10 seconds
   40-88 Km/hr (25-55 mph) in 20 seconds
3. **Gradability** - Maintain 64 Km/hr (40 mph) on 4% grade.
   Achieve 64 Km/hr (40 mph) in 305 m (1000 ft.) on a 4% grade.

Computer modeling confirms these goals can be achieved with a traction motor rated at 14.9 Kw (20 hp) continuous, and a two-minute overload rating of 29.8 Kw (40 hp).

4.1 System Requirements

To use the multispeed transaxle to best advantage, the entire propulsion system must be of optimum design. This means each component must be designed as an integral part of the system. Since the multispeed transaxle permits a more conservative motor design, motor and transaxle costs and complexity can therefore be optimized. The large torque multiplication in low gear permits reasonable acceleration without excessively high current to the traction motor. If peak current is limited the motor controller may be simpler and less expensive. This balanced component concept was applied to the system during the development of each component.

The original transaxle design, developed for an AC system, was a two-speed version which was considered inappropriate for a DC system. With only two-speeds, the traction motor would have to operate over a three-to-one speed range, requiring a relatively long shift time due to the high inertia and low slew rate of the DC motor. In addition the motor would be more difficult to build, requiring more care to achieve good commutation over a wide speed range. The decision was made to provide three transaxle speeds with 1.75:1 steps for an overall 3:1 change from high to low gear. This would require only a 2:1 speed range from the motor. The added complexity of the transaxle was quite small and the benefits to the motor quite large.

In choosing a traction motor for a near-term system, only three choices are available: the series wound, the permanent magnet and the separately excited shunt wound. The series motor has good low speed torque but requires a full range chopper and additional complexity to achieve regeneration. The permanent magnet motor is more efficient than the series wound motor, but still requires a full range chopper controller with the additional regeneration complexity. The separately excited shunt wound motor can be operated in the weak field condition without chopping armature current where it is inherently regenerative with no additional controller components. It is also efficient over a wide range of load and speed conditions. The motor need operate over only a 2:1 speed range with a 3:1 ratio in the transaxle for a 6:1 speed range overall. If the base speed of the motor corresponds to 10 mph then top speed is at least 60 mph. Regeneration would be available anytime above 10 mph.

The motor and transaxle complement each other well, but a controller capable of utilizing their advantages was needed. Since the motor is operated in field control at all times above a vehicle speed of 10 mph, reducing the power handling requirements of the controller is attractive. A typical controller, capable of chopping

350-400 amps continuously, can deliver approximately twice rated power for a 20 hp motor @ 108 vdc. (A near-term system would operate in the 96-120 vdc range).

With the three-speed transaxle, it should be possible to achieve acceptable acceleration from zero to 10 mph with only rated power, or 200 amps maximum. This cuts the chopper power requirements in half--within the capability of a single chopping transistor. Once in field control above 10 mph, a bypass contactor could handle the armature current and the field could be modulated to control armature currents to 350-400 amps. To take one further step, since the armature and field need not be chopped simultaneously, the bypass contactor for the armature could also be used to connect the field to the chopping transistor when operating in field control, eliminating a separate field chopper. This technique has been known previously in industrial applications for many years.
The system would consist then of: a three-speed transaxle; a separately excited shunt wound motor; a controller with a limited range chopper capable of rated motor torque to base speed in armature control, and then twice rated motor current to at least twice motor base speed in field control.

4.2 Motor

4.2.1 Description

A separately excited, field weakening motor is not new; many are already employed both for industrial application and as traction motors. Most of the traction motors are, in fact, industrial types. They are heavy, large and expensive. A motor as light, small, efficient and inexpensive as possible was needed. To this end a custom traction motor was designed and built by an Eaton Industrial Truck Division.

Specific design goals were: weight less than 200 lbs., efficiency at least 85% at rated speed and torque, a one hour rating of 20 hp, two minute rating of 40 hp for accelerating and hill climbing, and optimized for peak efficiency in the 12-15 hp weak field operating mode. These goals are based on vehicle performance predictions with a 3900 lb. gross weight in a modified Mercury Lynx vehicle. The decision was made to make a long frame motor with as small a diameter as possible. This would give good low speed torque as well as minimizing frame size, weight and inertia. The armature selected had a 5.75" diameter and in its original form a stack length of 4.5". This was increased to 6" to improve torque at low RPM and achieve a low base speed. It was still possible, with the long armature stack, to use machine-formed single-turn coils.

4.2.2 Separately Excited Traction Motor Specifications

1. Minimum 15.3 kW (20.5 hp) for one hour at base speed and above.
   Rating: 29.8 kW (40.0 hp) for two minutes at base speed and above.

   Field weakened range: at least 2.5:1.

2. Poles: 4

3. Direction of rotation: Clockwise (from output shaft end of motor).

4. Interpoles: 4

5. Base speed and rated torque: 1800 rpm @ 60 lb-ft

6. Maximum speed: 4500 rpm

7. Voltage: Armature - 108 vdc nominal battery voltage (97v at rated torque). Field - 70 vdc nominal for full field excitation.

8. Armature chopper: PWM transistorized. Limited to current for base motor torque.

9. Field chopper: PWM transistorized. 10A nominal for full field.

10. Frame: Steel and aluminum. Face mounting 10.25: diameter (excluding terminals and air duct). 17" max. length (excluding motor shaft).

11. Shaft details: Per ERC Drawing 50233-C (revised) 1/2-20 UNC-28 thread.

12. Mounting flange: Per ERC Drawing 49392-D.

13. Cooling: Fan forced through duct at commutator end of motor, exiting from shaft end through radial ports. Air must be filtered. Internal fan supplies most of needed air.

14. Temperature rise: Approx. 55°C; insulation: Class H.

15. Ambient temperature: -40°C to +40°C.

16. Efficiency goal at stated conditions: 85% at rated torque.

17. Weight: 180 lbs.

This reduces cost since the armature can be machine assembled to the commutator. This long thin armature has lower inertia than a short, fat one--important for synchronizing motor speed during gearshifts.

The 6" armature stack then requires a 6" field stack, consisting of four main poles and four interpoles. An initial attempt to produce a motor without interpoles was made, but at high load in the weak field condition the commutation was judged to be unacceptable. The field pole assemblies were made as small as possible to achieve the most compact design. Several iterations were made to optimize copper between main poles and interpoles. To provide sufficient flux path for the field a 6" long cylinder of 11/16" iron was needed, giving a final O.D. for the frame of 10¼". This is as small as practical, as little open space is available between pole windings for cooling air flow. The remaining frame is entirely of aluminum to save weight. The final weight of the motor with brush cover and auxiliary air inlet installed is 180 lbs.

To save energy, the auxiliary fan that provides cooling air to the motor would only be operated when motor temperature exceeded a design level. Since the motor is so compact, a small integral fan was added to keep some air moving through it when operating. This fan gives the motor a one hour rating of 16 hp at rated speed. Unless the operating cycle requires frequent high acceleration current or the ambient is particularly high, no auxiliary fan would be required. In addition, when the vehicle is not moving, the auxiliary fan would not operate unless the motor were already too hot.

4.3 Controller

4.3.1 Design and Operation

The controller is divided into three sections. The logic/power section, the vehicle DC-DC converter section and the contactor/relay section. The first section discussed here is the logic/power section. See Figure 4.3.1-1.

Based on the acceleration calculations, the controller need supply only enough current for rated motor torque in the armature chop mode in low gear. The current requirement is less than 200 amps and can be handled by a single power transistor. The advantages to the limited current armature control include considerably less heat generated while chopping, smaller bus capacitor requirements for smoothing, less logic and drive complexity to drive a single chopping transistor. It is relatively easy to include some protective circuitry to prevent transistor desaturation during overloads or to detect a failed switching device and shut down the system.

The switching transistor chosen was the Motorola MJ10201, a Darlington device with speed-up and anti-parallel diodes. Rating is 250v and 200 amperes. The package is capable of dissipating up to 500 watts. This device was just being sampled to potential customers in the last quarter of 1981 and several pieces were obtained for evaluation. Testing confirmed the units were rugged and well suited to this chopper application.

4.3.2 Controller Specifications

1. Type: Transistorized, PWM, armature and field control.

2. Rating: 350 amps @ 108 vdc nominal battery voltage.

3. Operating frequency: Variable, 0-5 KHz.

4. Inputs:
   a) from transaxle - motor speed, vehicle speed;
   b) from gearshift - forward, reverse, park gear, neutral;
   c) current demand from throttle;
   d) service brake;
   e) parking brake.
   f) charger

5. Outputs: to transaxle: first gear solenoid; second gear solenoid; third gear solenoid.

6. Operating modes: field current chop - up to 15 amps; armature chop - up to 175 amps; armature in bypass - up to 350 amps.

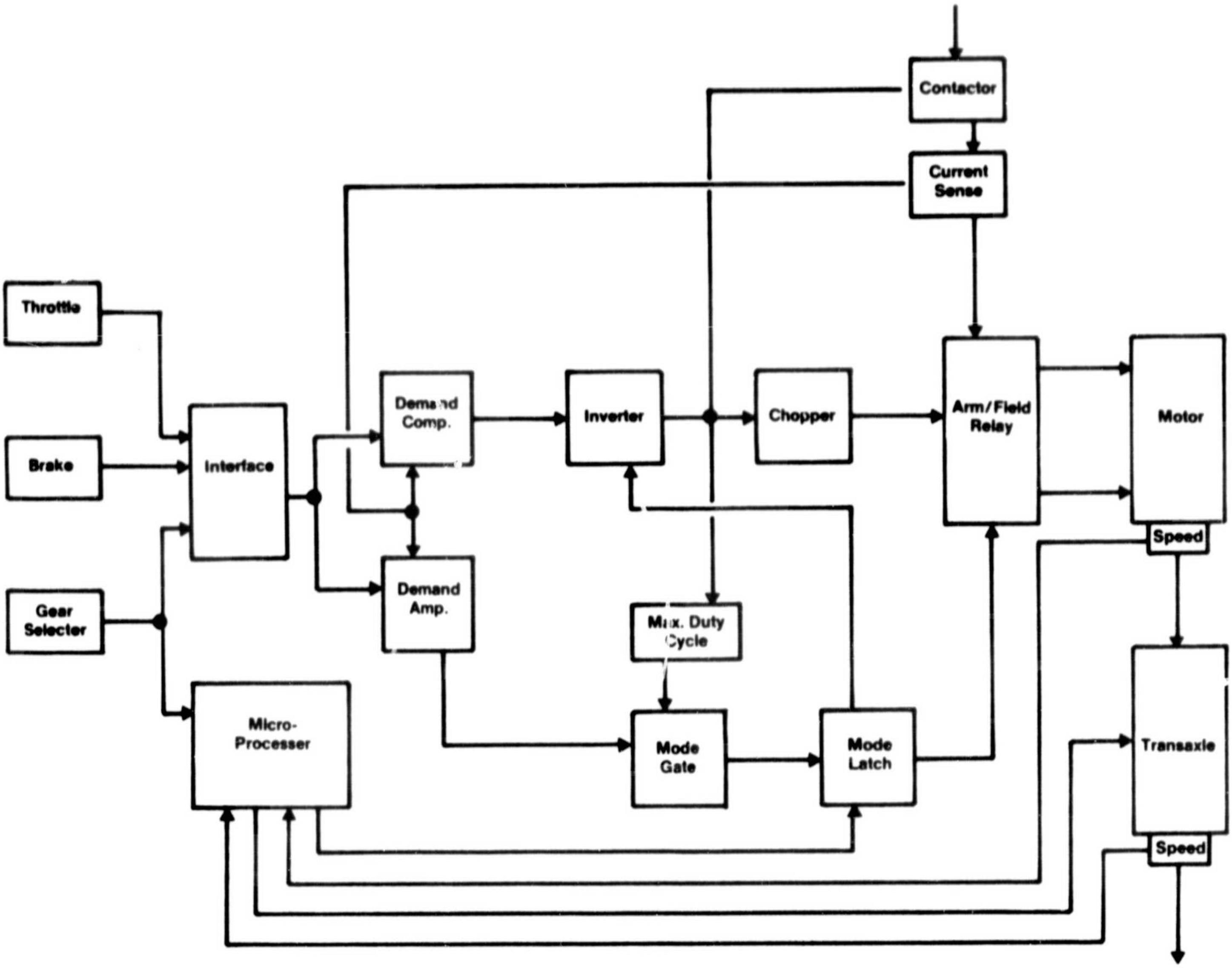
7. Size: L x W x H = 15¼" x 16½" x 9"

8. Ambient temperature: $-20^{o}F$ to $+140^{o}F$.

9. Cooling: cooled by natural ram air flow.

10. DC-DC converter to maintain auxiliary battery: 25 amps @ 12v from 108v input.

11. Microprocessor-based shift control to monitor motor and vehicle speeds. Provides motor synchronization and transmission shift signals.



Controller Logic/Power Block Diagram

Figure 4.3.1-1

The decision to rely on field control exclusively above motor base speed in low gear and through second and third gears led to the idea of using the same chopper for armature and field control. If the armature and field were not being chopped at the same time it should be possible to switch the chopper from one circuit to the other. A lab test on a small scale system, 1/3 hp, confirmed that full range control could be accomplished with one chopper and logic. As speed increases in armature control the chopper duty cycle increases until it reaches 100%. To increase speed further the armature is switched to the bus supply and the field to the chopper. The duty cycle then must decrease from 100% to increase motor speed. This is accomplished easily by inverting the drive signal to the chopping transistor when switching from armature to field control.

The chopper is a closed loop, current controlled, oscillator with a fixed hysteresis or ripple. When operating, the armature current is equal to the throttle demand with a constant magnitude of current ripple, approximately 25 amps. This is true when operating in armature or field control as the regulating is done by monitoring armature current only. The chopper frequency then varies from zero to a maximum of 5 KHz when in the armature chop mode and operates at approximately 30 Hz in the field control mode.

Current control is accomplished by means of a clamp on the throttle input to limit current to 175 amps in the armature chop mode and 350 amps in the field chop mode. Regeneration limit is accomplished the same way by means of a clamp on demand. Regeneration can take place only above motor base speed, 1800 rpm. To regenerate in the armature chop mode adds considerable complexity and with this system would only add regeneration capability to speeds below 10 mph, so was not provided.

There are two current limit protection systems, one detects current above 400 amps and the other monitors saturation voltage on the chopping transistor. If current exceeds 400 amps in the armature chop mode or the transistor begins to come out of saturation, the system will be shut down. This requires a system re-start to operate again.

The changeover from armature to field control is implemented when the chopping transistor reaches nearly 100% duty cycle. A comparator determines that demand still exceeds the operating point, and that combined with a 100% duty cycle enables a flip-flop to toggle. Several changes occur: the contactor is energized; the logic signal to the chopping transistor is inverted; the current limit is raised from 175 to 350 amps. Now the duty cycle of the chopper is decreasing to increase motor current in the field weakening operation. The chopper is now controlling from 3 to 6 amps while the armature is drawing up to 350 amps directly from the bus so that the controller efficiency is very high.

Control is strictly by armature current, which is proportional to motor torque. This means the throttle is a torque demand, but since the voltage is essentially constant, and power is volts times amps, it is also a power demand.

Current is sensed by means of a Hall-effect device on the armature power cable.

During the transistion from armature to field control, a power contactor is making and breaking the armature and field circuits. A period of current discontinuity that is sensed by the Hall device might interfere with the mode change and chopper control. To eliminate this problem, a timer generates a short pulse to the crossover comparator to mask out the discontinuity. If the logic signal were inverted at the same time as the power were applied to the contactor, the field would weaken causing the armature current to increase--generating a large torque pulse. This is eliminated by delaying the signal to invert the logic by the time it takes the contactor to close, approximately 90 mSec.

While in the field control mode the motor will continue to accelerate as the field is weakened, still controlling armature current. When the throttle is released, current demand drops, the field is increased and armature current drops. If the demand is reduced to a negative value, by application of the service brake, field current is increased until armature current becomes negative. Current is regulated by a clamp on negative current demand. The system will decelerate, regenerating power until the motor reaches base speed, at full field.

The transition from field to armature control is very much the reverse of the armature to field switch. When the chopper duty cycle reaches 100% full field, and demand is still less than the operating point, the comparator de-energizes the crossover contactor. During the transistion a timer again masks the current discontinuity and the logic inversion is delayed this time by 200 mSec because the contactor drops out slower than it pulls in. The current limit is reduced from 350 amps to 175 amps.

The motor field requires only 8-10 amps for full field excitation. When in the armature chop mode, the field is tied directly to the bus, allowing up to 20 amps to flow through a cold field winding. Not only is this energy lost, but field overheating could result. For this reason the main power contactor is closed only if the throttle is demanding more speed in the armature chop mode. At speeds below 10 mph the contactor will open and close in response to the throttle demand. This prevents unnecessary energy loss in the field while coasting with the chopper not operating. When in field control, the main power contactor is not permitted to open except in a case of system failure to remove power.

The controller utilizes both analog and digital logic. The digital logic is all of the CMOS type because of its low power requirements and relative noise immunity. The analog portion uses low-cost, dual-operational ampliers of the LM358 variety. This logic operates from a single-ended power supply for simplicity. To interface from the CMOS logic to the 200 amp main chopper a power field effect transistor was used. This makes for a very simple driver configuration using a single device to provide up to 10 amps of base current direct from a CMOS gate signal.

There are only two power supply voltages, 12v and 7v. All low level logic operates at 12v. The 7v supply provides only base current to the chopping transistor.

Testing confirmed the chopping transistor could operate without a negative base turn-off bias. To protect the chopping transistor from inductive spikes, a snubber is installed directly between the collector and emitter. This is a polarized snubber consisting of a 5μfd, oil-filled capacitor, a 5Ω 100 watt resistor and a diode in parallel with the resistor. This snubber absorbs current during the transistor turn off to prevent exceeding safe operating area voltage and current specifications. Since the main bus capacitors are not very close to the chopping transistors, a secondary bus capacitor was added at the transistor with a diode from the collector to the capacitor and a resistor to the main bus. Fast overvoltage spikes are absorbed by this capacitor which slowly discharges back to the main bus.

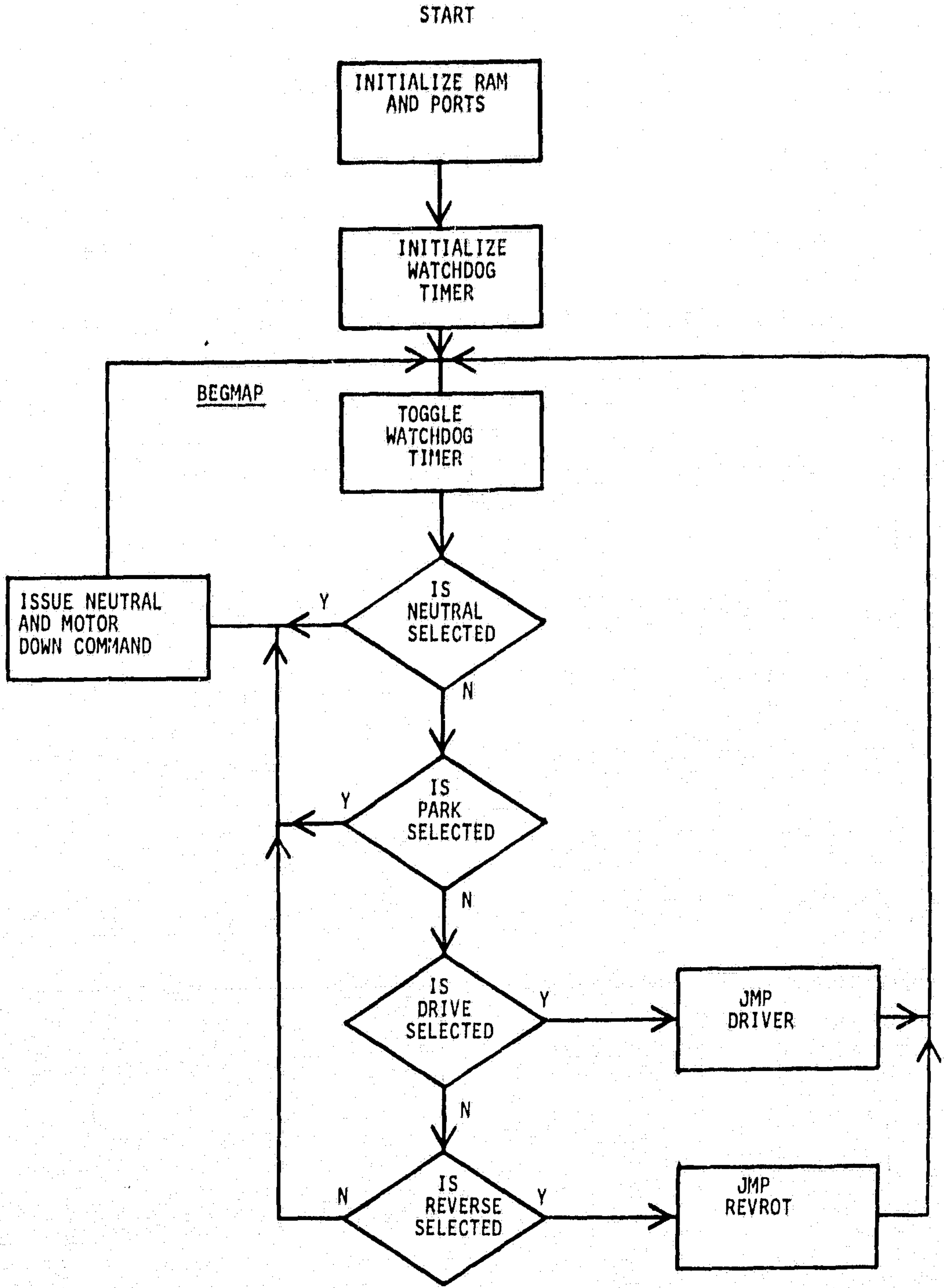
To provide a reverse gear, the motor field is reversed with the transmission locked in low gear only. The field current can be as high as 20 amps to an inductance of one henry. Switching this current with the 108v applied would require another large contactor. To use a smaller contactor the switching is initiated only when there is less than 3v at the field terminals. This is accomplished by monitoring the bus voltage when a forward to reverse, or vice versa, shift is made. A shift signal generates a zero current clamp on demand causing the motor to come to a stop and the main contactor to open. When the current circulating in the field dies out and the voltage is below 3v, a small relay then reverses the polarity of the field.

There are two resistive relays on the main logic printed circuit board to interface the vehicle 12v system, which must be fully isolated from the high voltage battery system. One is activated by the positive current limit clamp and lights a yellow LED on the instrument panel, informing the driver that maximum power is being utilized--an inefficient operating condition. The other is used to cause a system shutdown. If a logic or power switching failure occurs, the relay will remove ground from a relay coil in the 12v ignition system, causing the main power contactor to open and requiring a re-start of the vehicle.

4.3.3 Microprocessor Functions

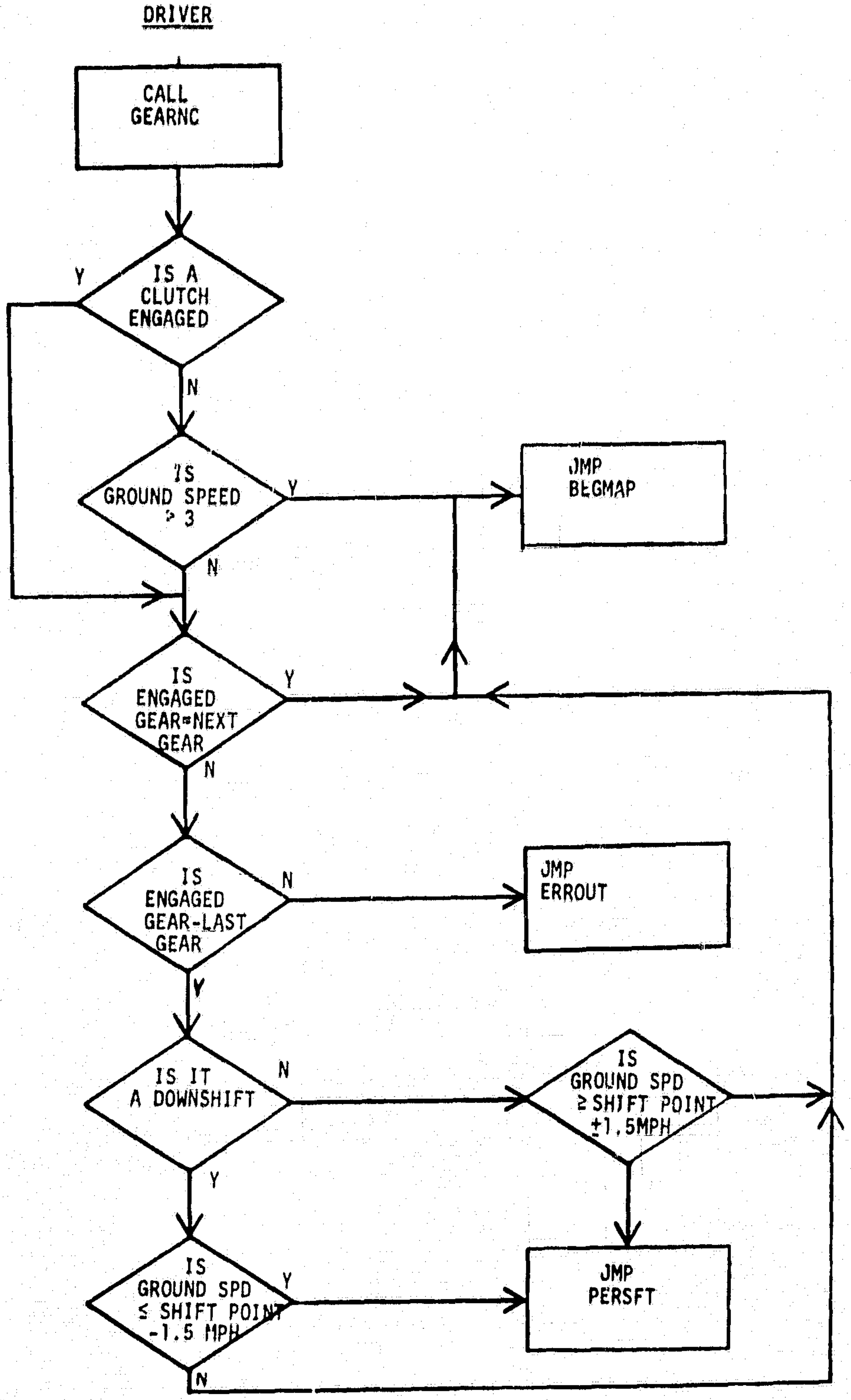
The microprocessor is responsible for performing all shift functions. It determines what gear is selected by the operator, whether it is appropriate, and whether the system is in a normal operating mode. It measures ground speed and motor speed constantly and performs the synchronized shifts up and down through the gears. It detects motor overspeed and loss of speed pickup to prevent motor damage.

The flow chart for the microprocessor program follows in Figure 4.3.3-1.

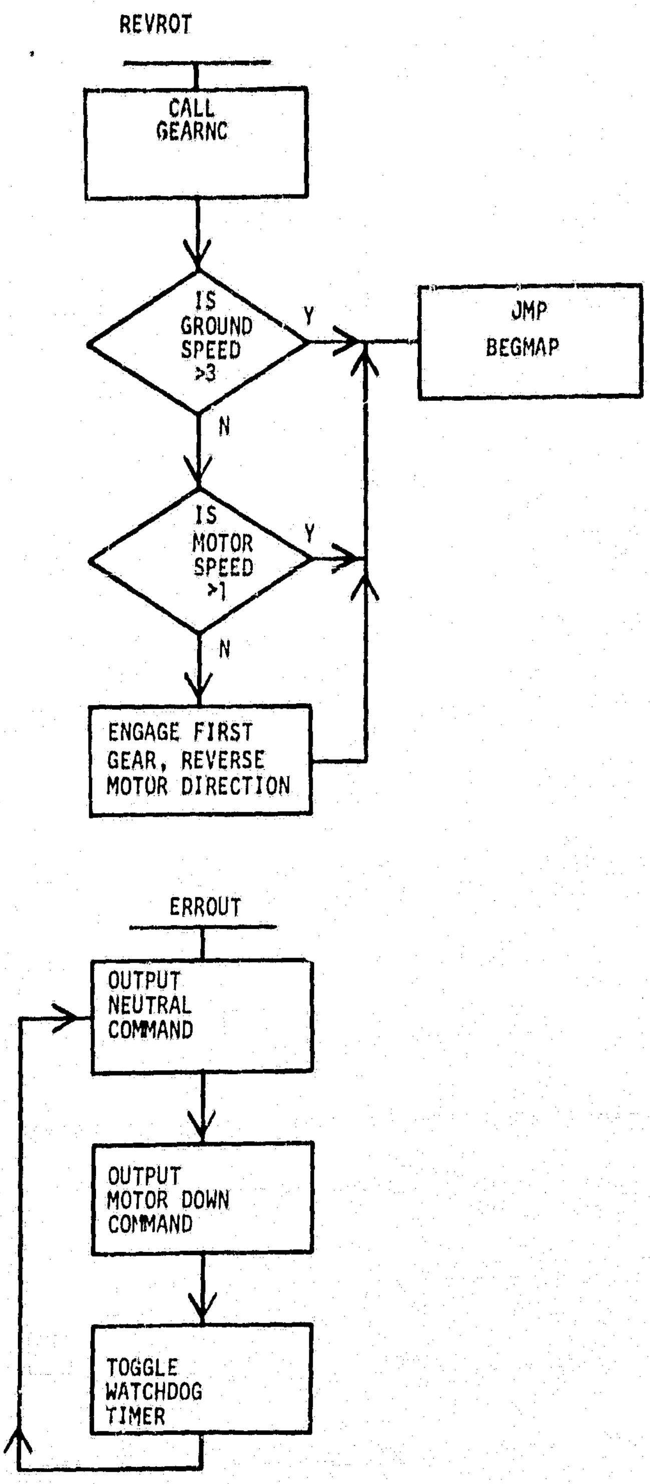


Microprocessor Flow Chart

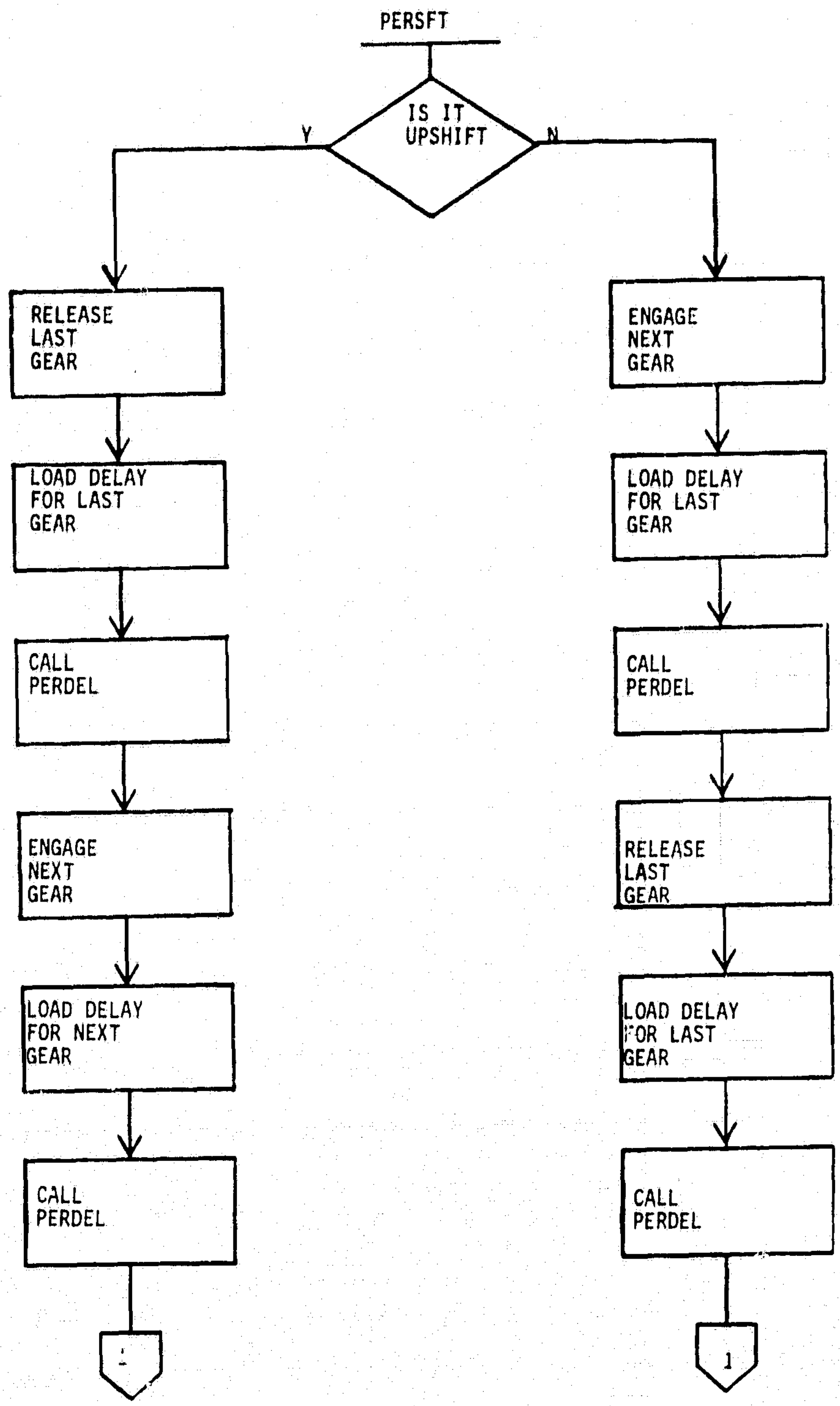
Figure 4.3.3-1



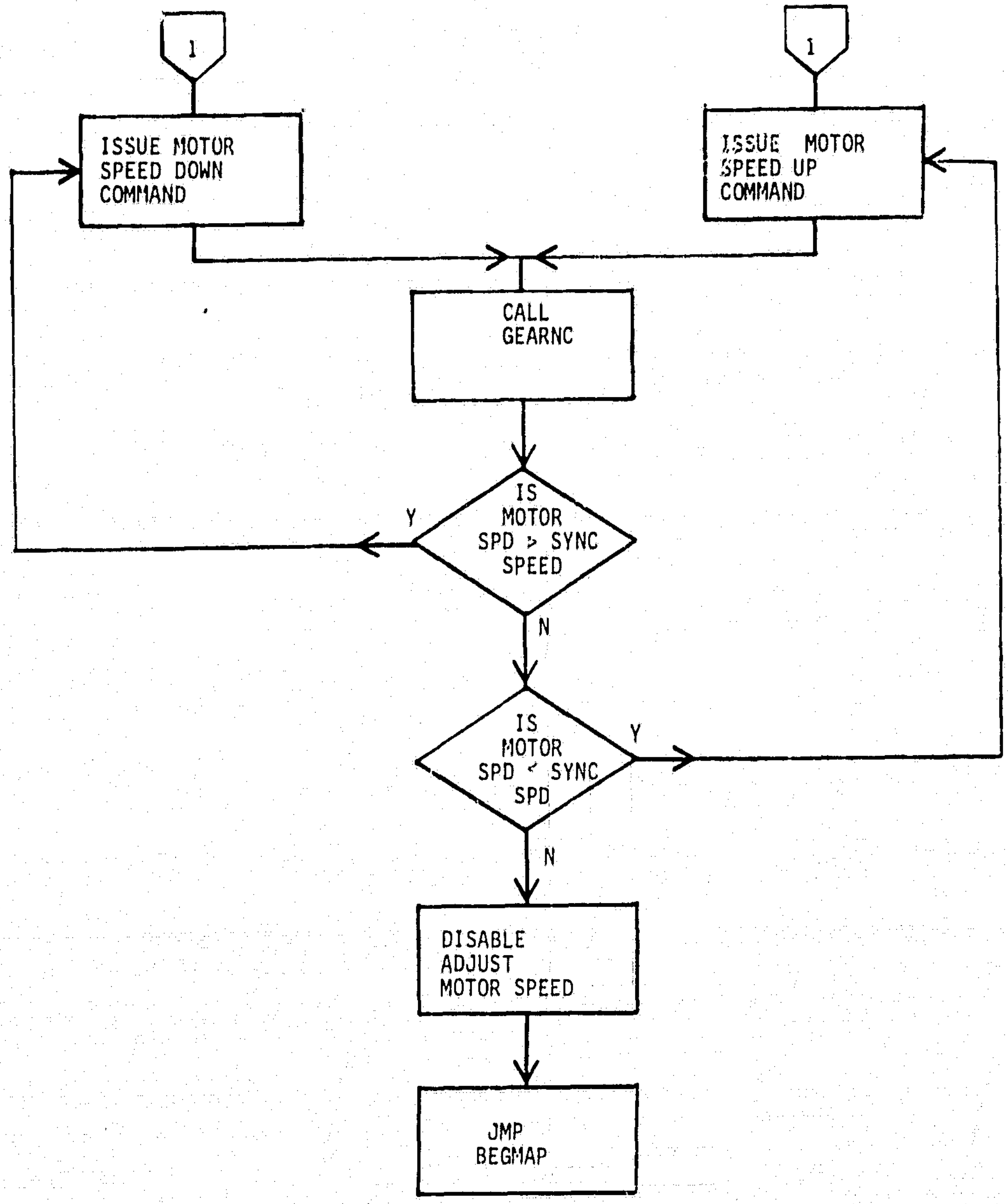
Microprocessor Flow Chart Continued



Microprocessor Flow Chart Continued

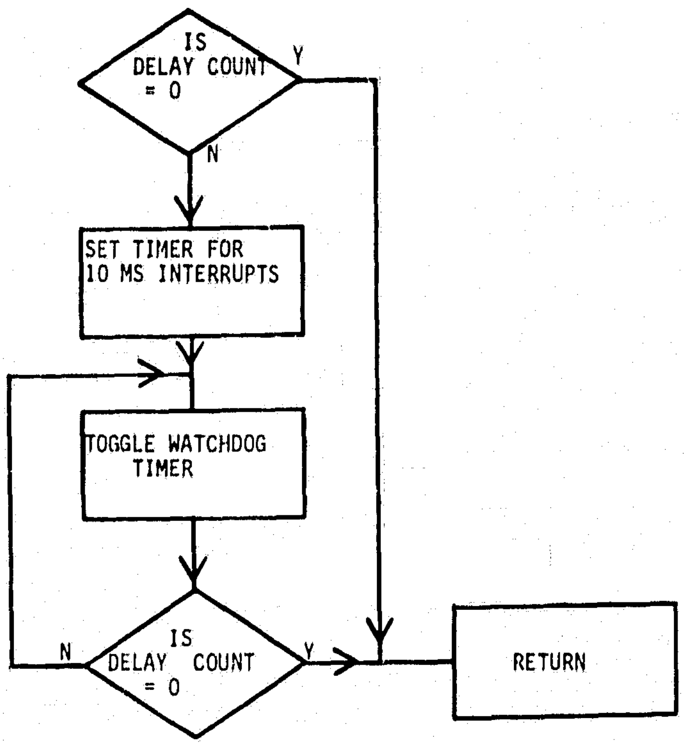


Microprocessor Flow Chart Continued

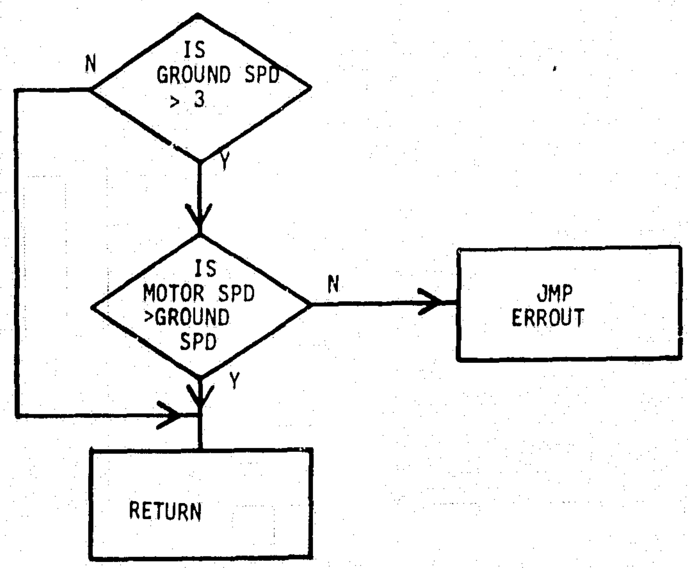


Microprocessor Flow Chart Continued

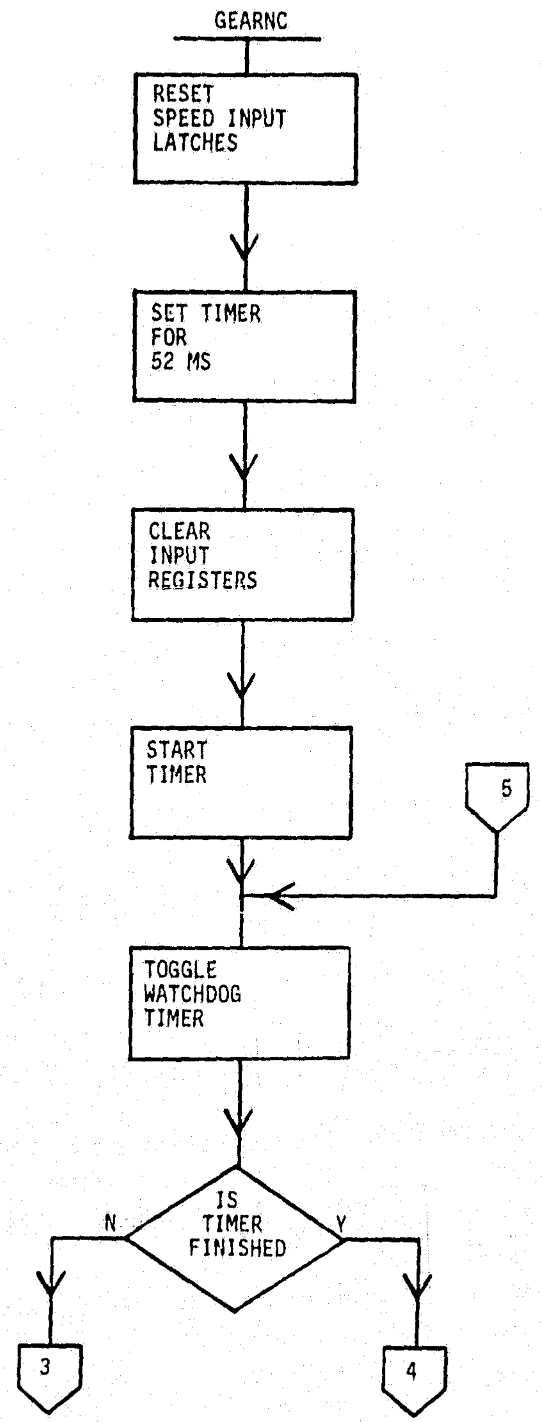
PERDEL



MOTCK



Microprocessor Flow Chart Continued



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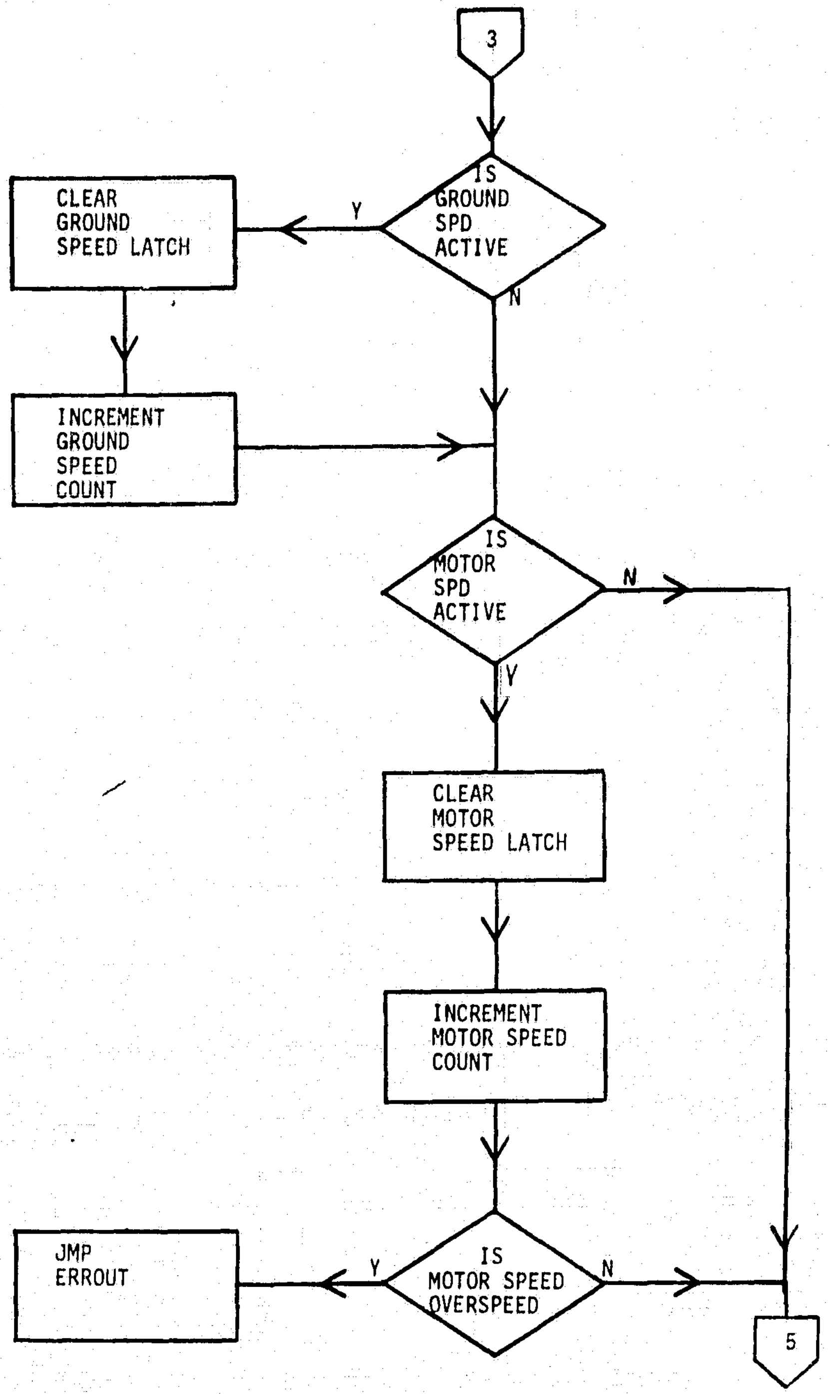
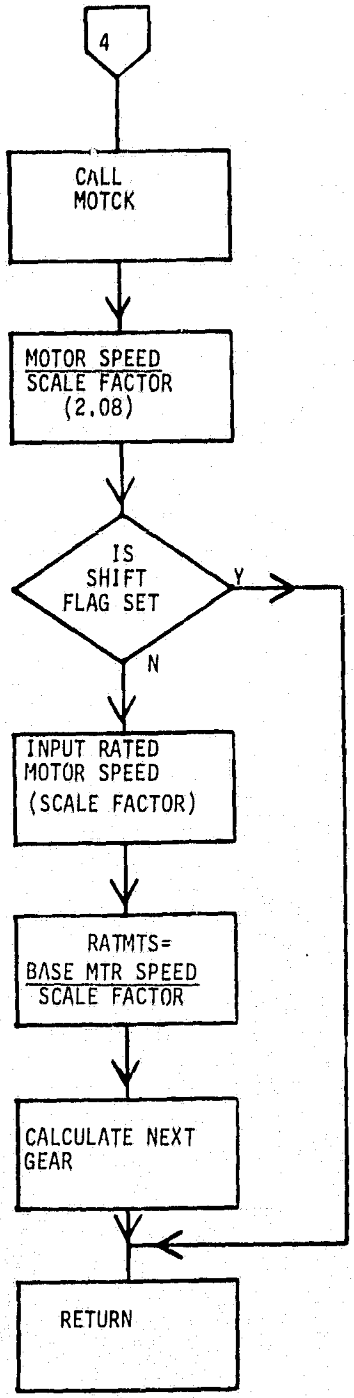
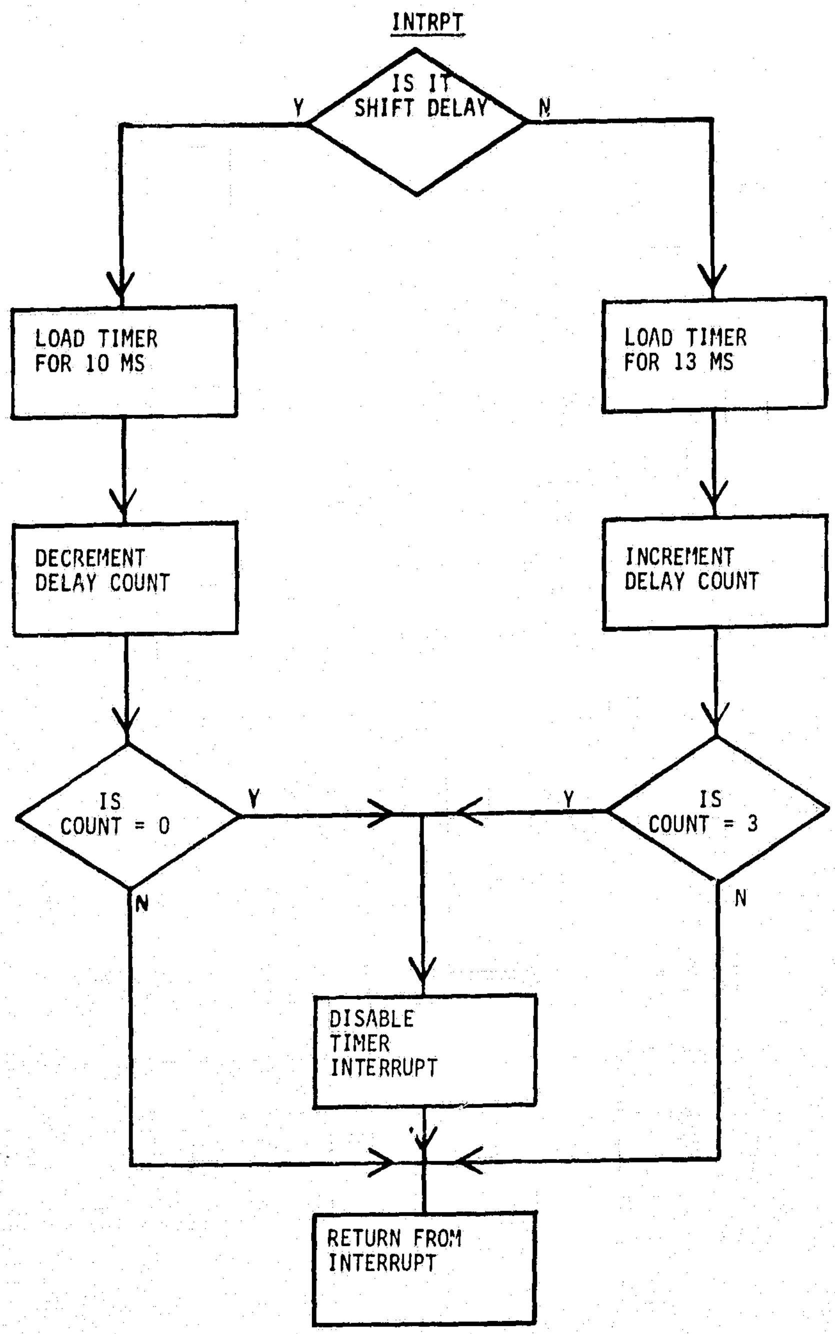


Microprocessor Flow Chart Continued



Microprocessor Flow Chart Continued



Microprocessor Flow Chart Continued

BEGMAP ROUTINE (MAIN LOOP)

The software is configured as a main loop (called MEGMAP) which continuously updates the watchdog timer and checks the position of the shift lever. If the shift lever is in drive, the "DRIVER" routine is called as a subroutine, and when reverse is selected, "REVROT" is called. Under any other condition, park, neutral or the absence of all shift lever signals, a motor speed down and neutral command will be issued.

DRIVER ROUTINE

When drive has been selected, "DRIVER" is called by the main loop. Upon entering this routine, ground and motor speed are sampled, and the "next" gear is calculated by routine "GEARNC." If a gear is not currently engaged and ground speed is below 3 mph, then the first gear clutch is engaged. Otherwise, a return to the main loop will be executed without action being taken. If the "next" gear is the same as the "last" gear, no shift is required, and it will return to the main loop.

If a clutch is engaged and it does not equal the "last" calculated gear, then an error condition exists and a jump to "ERROUT" takes place. If a shift is indicated and the ground speed is 1.5 mph above or below (upshift or downshift) the nominal shift point, a shift is performed by "PERSFT," which returns to the main loop.

REVROT ROUTINE (REVERSE)

"GEARNC" is called to obtain ground and motor speed. If ground speed is less than 3 mph and motor speed is zero (0), the fist gear clutch and a reverse motor direction command is sent and a return to the main loop is executed.

GEARNC ROUTINE

This routine inputs the ground and motor speed signals for a period of 52 milliseconds and checks for a motor overspeed condition. If an overspeed occurs, a jump to "EROUT" is executed. The onboard timer is interrupt driven to allow the processor to sample speeds and update the watchdog timer.

After sampling, the motor speed is again checked for overspeed. Two (2) motor speeds are maintained: one is the raw speed and the other is divided by a scaling factor to reflect directly the axle speed in third gear. If a shift is in progress, a return to the calling routine would be executed at this point. If not, a scaling factor is read from the external straps to determine rated motor speed (shift point). The rated motor speed (RATMTS) is divided by the ratio for each gear (three gears) until the result is greater than ground speed. The gear number that "fits" is retained as the "next" gear. A return to the calling routine is now executed.

PERSFT ROUTINE

The "PERSFT" routine is executed from "DRIVER" routine when a shift is required. A flag, which was set in the "DRIVER" routine, indicates if an upshift or downshift is to be done. A time delay is used to compensate for the apply and release time for each clutch. The actual time of release and engagement of the clutches can be altered to provide time for the motor to synchronize just prior to clutch engagement. The sequence of events for an upshift is: release the "last" clutch; load the delay time and call "PERDEL"; after delay, engage the next clutch; load the delay time; after delay, take control of the motor and issue a motor speed down command; sample speeds (call GEARNC) until motor reaches synch (motor speed up/down commands are altered accordingly); return motor to manual control and return to the main loop.

The downshift is the same except the next gear is engaged prior to the last gear being released.

PERDEL ROUTINE

This routine receives the delay time from the calling routine and sets the internal timer for 10-millisecond interrupts. The watchdog timer is updated, and the delay count is checked until it reaches zero (0). The delay count is decremented on each interrupt. When the delay is finished, a return to the calling routine is executed.

ERROUT ROUTINE

"ERROUT" causes an orderly shutdown of the vehicle in the event of a motor overspeed or an incomplete shift. All clutches are released (neutral), a motor speed down command is sent, and the watchdog timer is updated. This is an endless loop, and the only way to exit is to bring the vehicle to a stop and power down.

INTRPT ROUTINE

The internal timer is used alternately for shift delay timing and speed sample window timing. The timer interrupt is enabled by the calling routine after the timer has been loaded. A flag is used to indicate a shift delay or a speed window. During a speed window the timer is set to interrupt at 13-millisecond intervals and is reloaded on each timeout until four (4) interrupts have occurred. After the fourth timeout, the timer is disabled and the loop count is set to zero. For a shift delay the timer is set for 10-millisecond interrupts, and the loop count is decremented until it reaches zero. At that time the timer is disabled. In both cases a flag is set by this routine to show the time interval is complete.

4.3.4 DC-to-DC Converter

The DC-to-DC converter supplies the isolated 12v and 7v supplies for the logic section as well as 12v to maintain the vehicle auxiliary battery. Output requirements for this section are:
12v @ 25 amps for the vehicle 12v system
12v @ 2 amps for the controller logic
7v @ 10 amps for the chopper base drive.

All of the above outputs are isolated from each other and from the 108v traction battery system.

DC-to-DC Converter Block Diagram

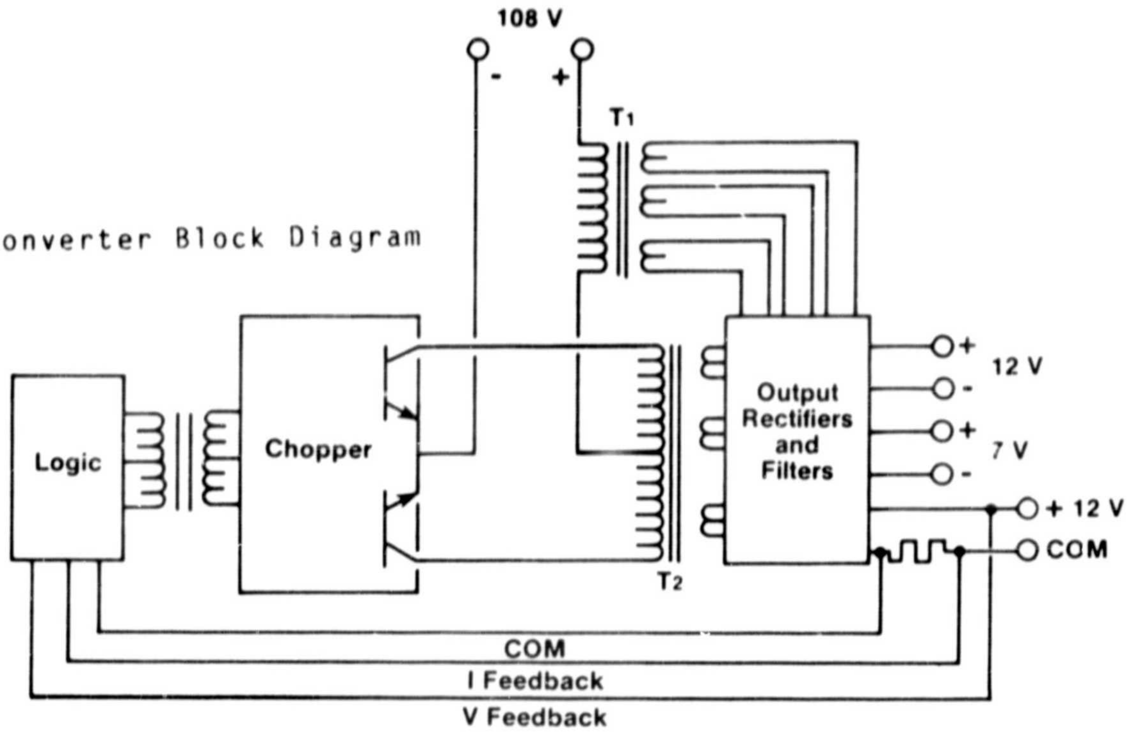


Figure 4.3.4-1

This power supply consists of a conventional two-transistor, push-pull parallel inverter. It features a coupled inductor (T1) whose primary is on the input side of and in series with the converter input, and whose multiple secondaries are in parallel with each of the supply outputs.

Operation of this circuit is described as follows:

- When both transistors are OFF, no primary current can flow. Energy which is trapped in the coupled inductor primary is seen as current in each of the coupled inductor secondaries; thus, each secondary is clamped to its output voltage. In this mode of operation, if any output is loaded more heavily than the others, its T1 secondary winding will "hog" the energy stored in T1, since its secondary voltage will tend to be lower than the other secondaries' voltages.

- When either transistor is ON, current flows through the inductor primary to the transformer primary T2. In this mode of operation, the T1 inductor secondary voltages are reversed and, thus, are blocked off by their series diodes. Current is supplied to the outputs by the T2 transformer secondaries, which, when conducting, are also voltage clamped to their outputs. Thus, if any output is more heavily loaded than the other outputs, it will likewise "hog" current from the other outputs.

- In either of the above cases, step changes in the load at any output are immediately seen and responded to by inductive elements in the input section. In addition, if these step load changes occur on unregulated outputs, the load current supplied to the regulated output will undergo a step change and, thus, the regulator section immediately sees and responds to load changes on the unregulated outputs.

. This excellent cross regulation between multiple outputs, as described above, is ideally suited to the severe step response requirements for this drive. The PWM chopper base drive can require up to 10 amps instantaneously, the T1 stored energy can provide power immediately to the base drive even when the converter transistors are off.

Other advantages to this type of converter are as follows:

. Input current rate of change is limited by T1 so the transistors are not subjected to current spikes.

. Transistor on-time and storage-time matching is not critical, as the T1 inductor protects the drive against slight volt-second mismatch in the T2 primary halves.

. The output current is continuous, so output capacitor requirements are small.

. The T1 primary winding blocks all but the minimum design bus voltage from the T2 primary and, thus, maximum transformer utilization is achieved on T2.

. Low peak inverse voltages occur on the output rectifiers and, thus, low dissipation Schotky rectifiers can be used in the 12v auxiliary output.

. All outputs are isolated from high voltage and each other.

The converter is designed around a single integrated circuit, the TL-494. This circuit provides several functions important to an effective converter. There are two comparator inputs for feedback to regulate voltage and current separately. The circuit has outputs to drive a push-pull type load. The drive signals have built-in, adjustable, anti-overlap delays. There is a soft start provision for the output to ramp up slowly from 0% to maximum duty cycle and an instantaneous current limit to shut down the chopping transistors in case of short circuits.

The output to the auxiliary battery is the one used to provide feedback for regulation. The converter will maintain the setpoint voltage, typically 14.4 volts, up to its current limit, at which point the voltage will begin to fall off smoothly.

4.3.5 Contactor/Relay Box

The third section of the controller is the contactor/relay box. These components were separated from the small signal logic because of the chance of damage to the logic when the contactors are breaking large currents.

The main power contactor is rated to break 400 amps at 140 VDC. It has magnetic blowouts and arc chutes with double breaking contacts. It was selected to operate routinely with fault currents since this is a prototype controller.

The crossover contactor is a double pole, double throw type that is used to connect either the armature or field to the chopper with the other motor winding connected to the main bus. This contactor will carry 350 amps continuously but is not rated to interrupt more than 72v. When the contactor is changing modes, it is in parallel with the main chopping transistor which is full on, or saturated at approximately 2v. Little energy is dissipated in the arc that occurs at crossover. In addition there is a free wheeling diode in parallel with the armature at all times to allow the current to continue to flow even when the contactor is opening.

The field reversing contactor is rated at 20 amps, has magnetic assist in breaking but cannot interrupt the arc of field current with the one henry inductance. The logic section does not permit this contactor to open or close until the voltage on the field winding has fallen below three volts. With this voltage sense a much smaller contactor can be used for field control than would be required with full voltage applied while switching. As in the armature circuit, there is a freewheeling diode in parallel with the field but on the primary side of the contactor where the polarity does not change.

One additional relay was added to provide a set of contacts to activate the vehicle backup lights. This relay coil, in parallel with the reversing contactor coil, was necessary because a new gear selector was installed in the vehicle with no backup switch.

The complete controller package is 15¼" x 16½" x 9" and can be removed as one unit or each piece separately.

In addition to the controller there is an interface box, mounted in the passenger compartment, that connects the vehicle 12v system to the isolated traction system through relay logic. The vehicle ignition switch provides 12v power when turned on and pulls in a latching relay when turned to the start position. This relay coil is connected to two interlocks for safety. If the charge hatch door is open the relay coil is not connected to ground and cannot latch on. If the charge cable is connected the AC power pulls in a relay in the on board charger which removes 12v from the ignition switch primary, preventing the vehicle from starting. If a logic failure occurs, the vehicle controller can also open the latching relay and shut the system down. The interface box has outputs to: start the DC-to-DC converter that powers the logic and charges the 12v auxiliary battery; start the hydraulic pump on the transaxle; and operate the battery box venting fan while the vehicle is operating.

Also located in the interface box is the 12v system low voltage warning detector to indicate the auxiliary battery is not being charged, and the motor temperature monitor to activate the auxiliary cooling fan for the motor when the temperature exceeds a predetermined value.

4.4 Transaxle

4.4.1 Objectives

The objective was to conceptualize, design and build a transaxle suitable for a near-term DC electric vehicle propulsion systems. The design was to be based on the earlier Eaton two-speed transaxle design for the Phase 2 AC Propulsion System, developed under contract DEN3-211.

As the ratio step of the two-speed design was too broad to be compatible with effective control of DC motor power by field weakening, a three-speed design was necessary. This would provide the required performance with much less strain on the motor, offer higher overall system efficiency, and be compatible with a greater variety of DC and AC propulsion systems.

Another design goal was simplicity and low manufacturing cost; available hardware was to be utilized as much as possible to meet the design goals and requirements.

4.4.2 Specifications

General

In-line transmission and differential gearing.
Magnesium castings for housing and chain case.
Reversing by traction motor reversal.
Neutral gear.
Mechanical parking latch.
Motor speed to be less than 500 rpm from synchronous when clutches are applied.

Ratings

Power, max, intermittent:	30 Kw (40 hp)
Power, continuous:	15 Kw (20 hp)
Motor speed, max:	4500 rpm
Input torque, max:	190 Nm (140 lb-ft)
Input torque, continuous:	82 Nm (60 lb-ft)
Regeneration required only in second and high gears	
Design life:	4800 hrs or approx. 160,000 Km (100,000 mi)

Ratios

Overall in low:	12.76:1
in 2nd:	7.27:1
in high:	4.16:1
Chain drive:	1.36:1
Planetary ratios in low:	3.07:1
in second:	1.75:1
in high:	1:1
Final reduction:	3.07:1

Hydraulic System

Independent 108 vdc motor driven oil pump

Pressure, max:	6.8 bar (100 psi)
Fluid:	Dexron II
Capacity:	3.8 ℓ (4 qts)

Cooling

Naturally self-cooled.

Dimensions and Weight

Between left and right U-joint flanges:	508 mm (20")
Width, front to back, including chain case:	470 mm (18½")
Height:	273 mm (10.75")
Center-to center, motor-shaft-to transaxle shaft:	244.6 mm (9.63")
Weight:	36 Kg (80 lbs), wet

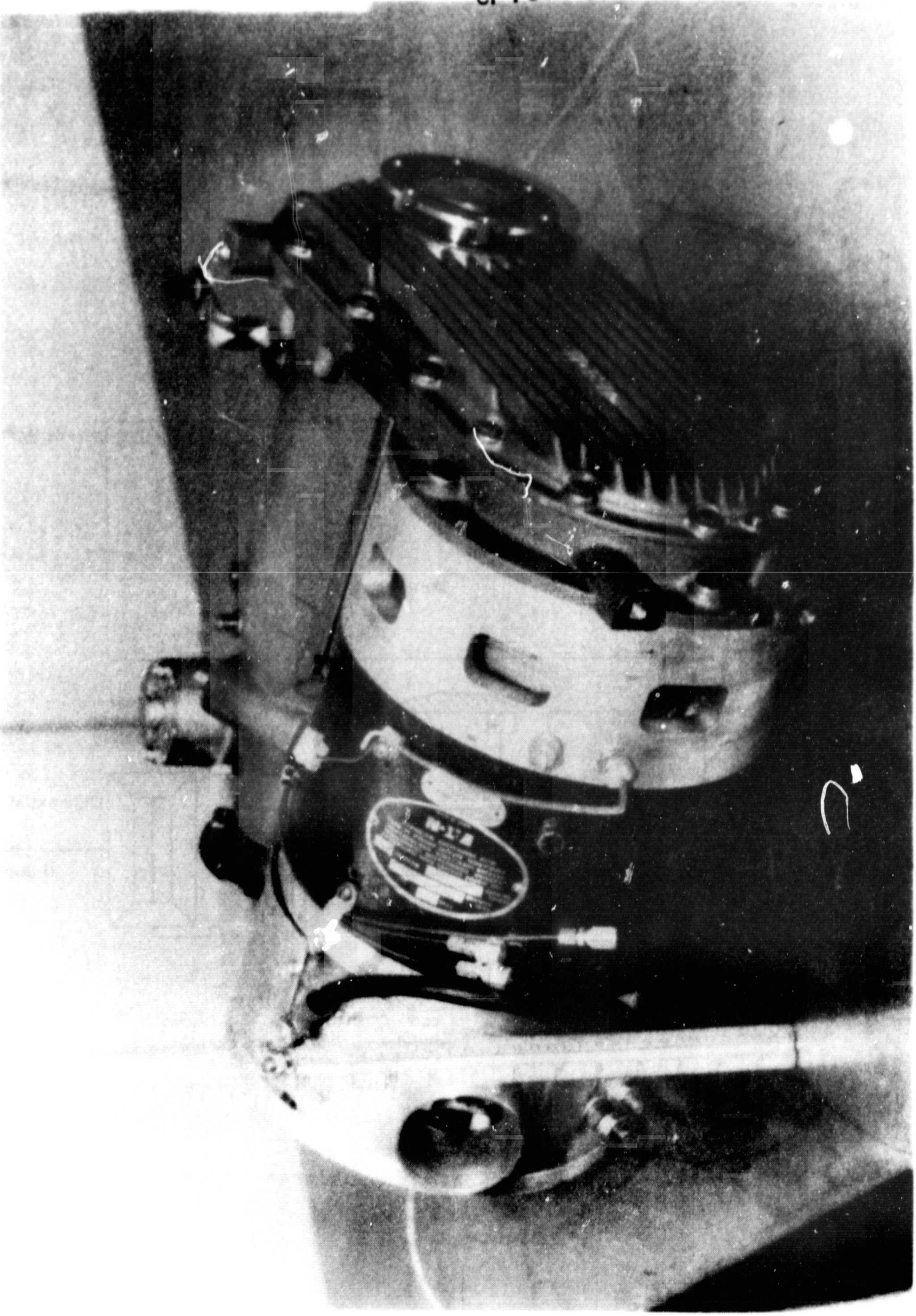
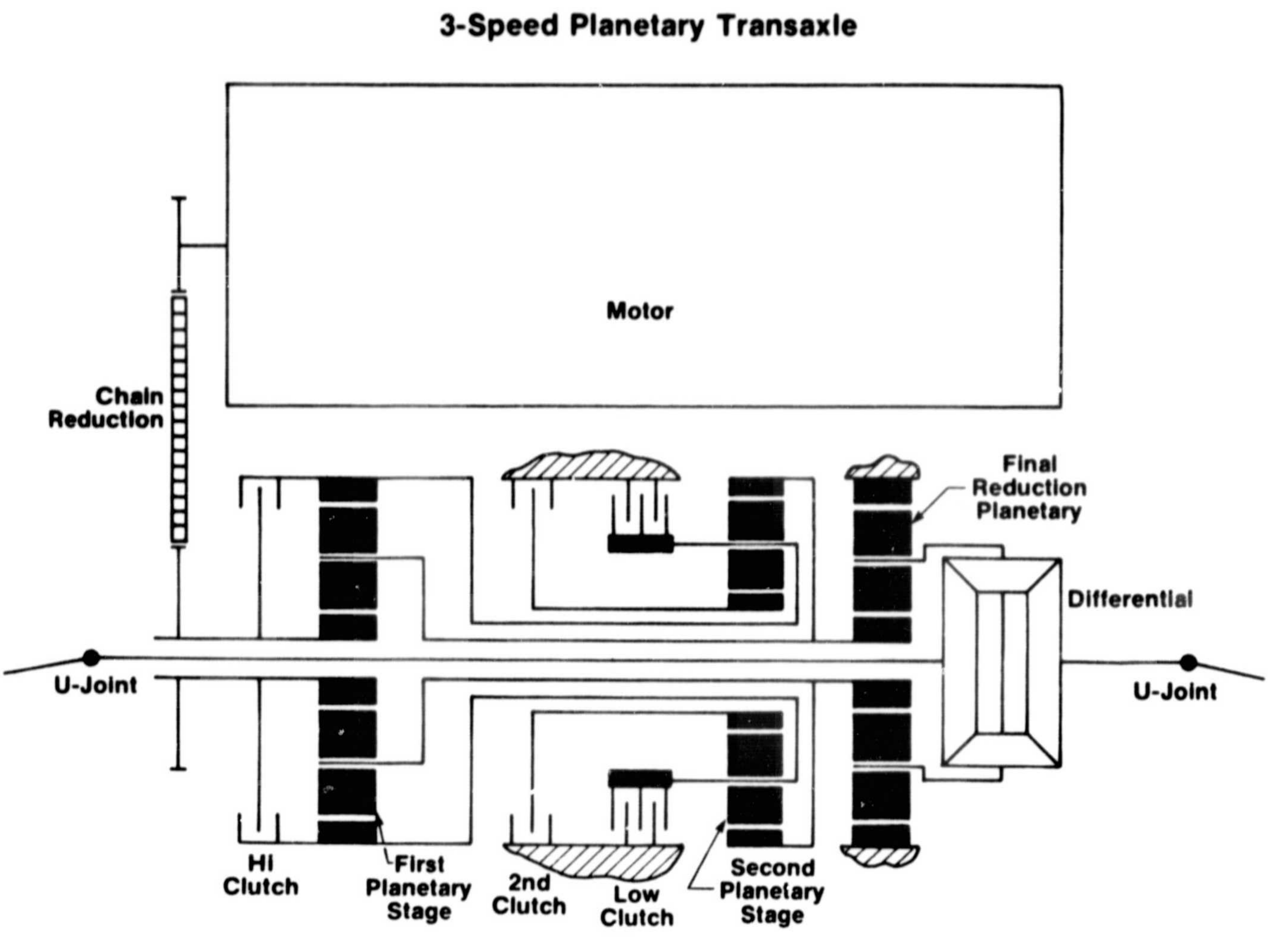


Figure 4.4.2-1 Trans/Axle/Motor Assembly



Transaxle Schematic Diagram

Figure 4.4.2-2

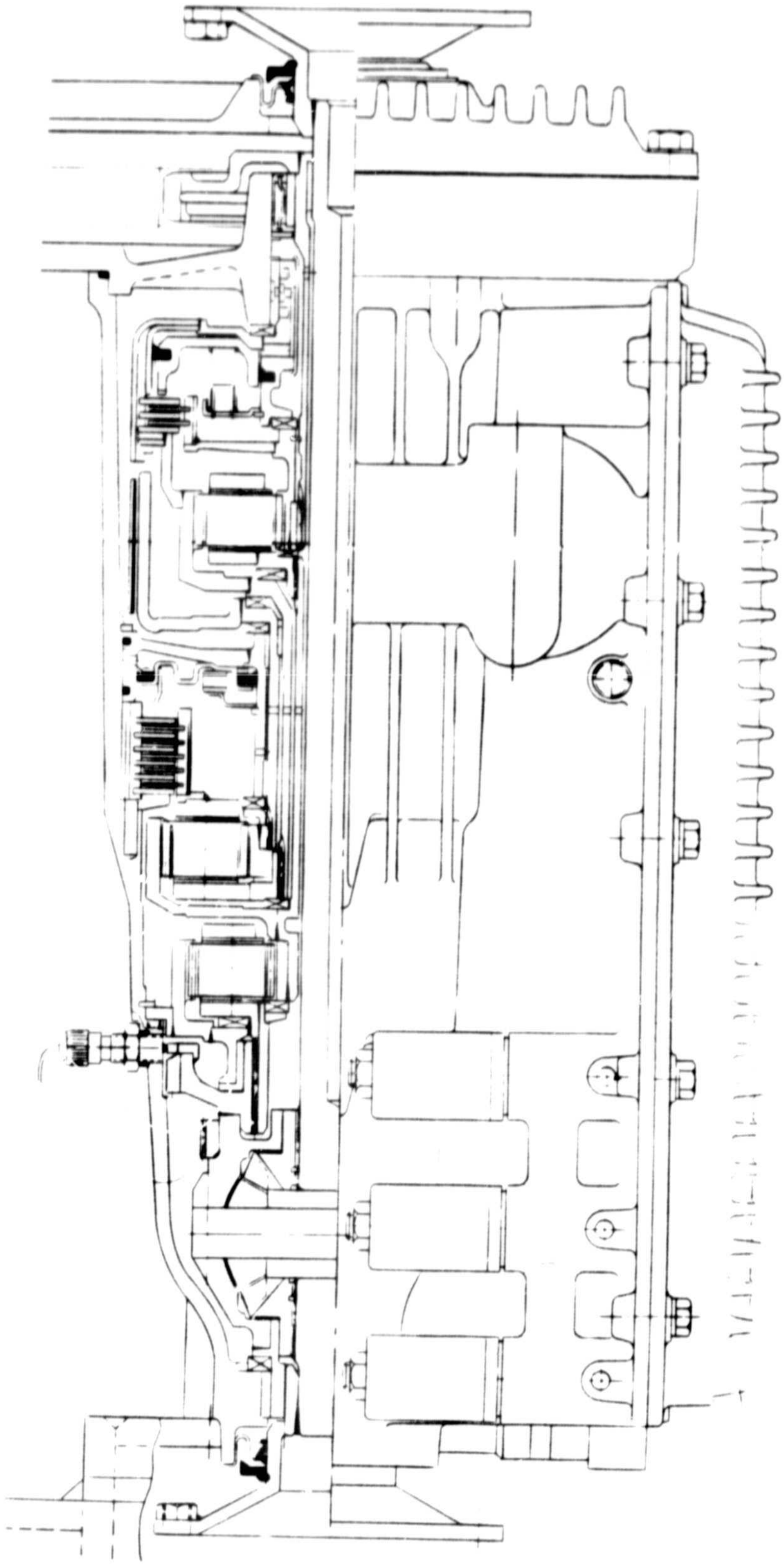


Figure 4.4.2-3 Partial Layout of Three-Speed Design

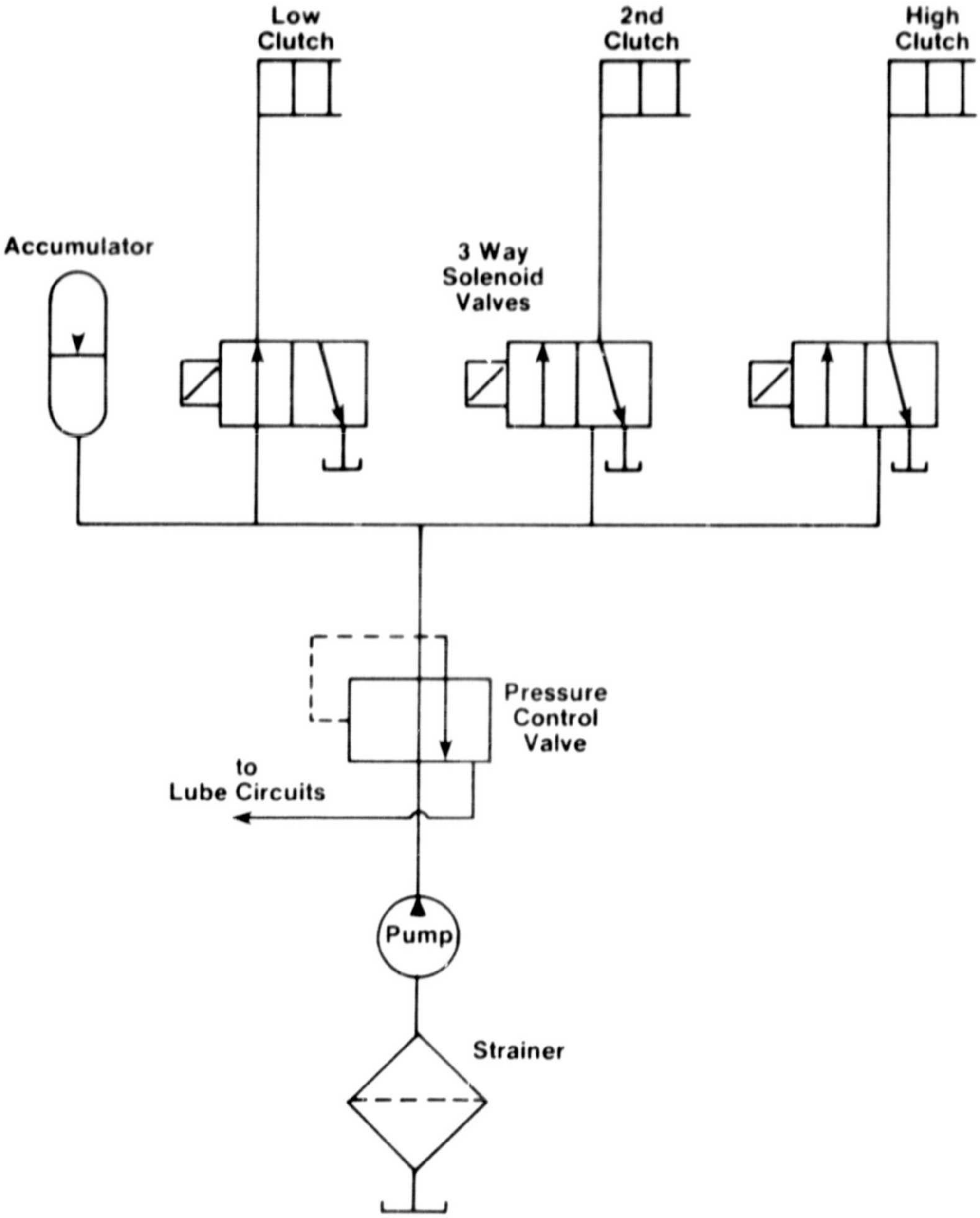


Figure 4.4.2-4 Transaxle Hydraulic System Schematic

4.4.3 Mechanical System

The basic function of the transaxle is to transmit and match mechanical power from the traction motor to the driving axles of the vehicle, and to serve as structural support for the motor. The traction motor is independently cooled, hence, unlike in the AC two-speed system, the transaxle is not required to dissipate the traction motor's rejected heat.

An external view of the transaxle/traction motor assembly is shown in Figure 4.4.2-1 and a cross-sectional schematic in Figure 4.4.2-2. Referring to the latter, the drive from the motor is by an advanced Morse Hy-Vo(R) chain drive to the sun gear of the first planetary stage.

The chain drive was retained from previous designs for its high efficiency, low noise, compact design, and low weight and cost (compared to idler gears spanning the same center distance). Also the reduction ratio, currently 1.36:1, is more readily modified, and so is the center distance (to accommodate a larger motor, for instance) by substituting alternate sprockets and/or chain housing. The chain drive is also less sensitive to component deflections and permits somewhat wider manufacturing tolerances.

The chain housing and finned cover serve as an effective oil cooler, as chain lube oil is sprinkled over large, cool wall areas before returning to the sump.

In low gear operation, the low clutch is applied, grounding the ring gear of the first planetary stage. The carrier, as the output of this stage, drives the sun gear of the final reduction planetary. The ring gear of that planetary is permanently grounded; the carrier, as output, drives the differential carrier and consequently both axles. The second planetary stage does not transmit any power in low gear operation.

Referring the Figure 4.4.2-2, R_1, R_2 and R_3 are the ring gears of the three planetary gearsets. S_1, S_2 and S_3 are the sum gears.

The speed reduction ratio in low gear, with two simple planetaries in series, is:

$$(R_1/S_1 + 1)(R_3/S_3 + 1) = (\frac{62}{30} + 1)^2 = 9.4:1$$

and overall reduction (including chain ratio):

$$\frac{42}{31}(9.4) = 12.742:1$$

In second gear, all three planetary stages transmit power. The second gear clutch (actually a band) is applied, grounding the sun gear of the second stage planetary. Power flows over two parallel paths: from first stage carrier to final stage sun and from second stage ring gear and carrier back to first stage ring gear. The resulting efficiency loss due to power recirculation is rather small; calculated and measured overall efficiency in second gear is approximately the same as that in low gear. The speed reduction ratio in second gear is:

$$(1 + R_1/S_1 - R_1R_2/(S_1(R_2 + S_2)))(1 + \frac{R3}{S3})$$

$$= (1 + \frac{62}{30} - 62 \times 74/(30(74 + 42)))(1 + \frac{62}{30}) = 5.361:1$$

and overall ratio:

$$\frac{42}{31}\ (5.361) = 7.265{:}1$$

In third gear operation the first planetary stage is locked up by engaging the high clutch. Power flows from the first stage carrier to the final reduction sun gear; no power is transmitted by the second stage gearing. The speed reduction ratio in high gear is:

$$R_3/S_3 + 1 = \frac{62}{30} + 1 = 3.067{:}1$$

and the overall ratio:

$$\frac{42}{31}\ (3.067) = 4.155{:}1$$

Reverse ratio is obtained by reversing the traction motor rotation. The speed reduction ratio is that of the low forward gear, 9.4:1, or 12.742:1 overall.

A partial layout of the three-speed transaxle/motor assembly is shown in Figure 4.4.2-3.

The gear and clutch elements have been adapted from several current production automatics, through rearrangement and rework of production parts and some custom-made splined components. Extensive electron beam welding was used, generally as a final operation.

The housing material is magnesium AZ92A-T6, as in the earlier two-speed design. This permits a one-third weight reduction from aluminum in the same volume, without sacrifice in strength.

Total weight of the four castings (machined) in the assembly is 18 lbs. No sealer was used on the castings. Manganese chromate dip treatment per MIL-M-3171, Type 3 specification was applied to all four castings (after machining) for corrosion protection.

4.4.4 Hydraulic System

The hydraulic system performs clutch actuation functions and provides lube and cooling flow to transaxle components. Figure 4.4.2-4

An independent 108v DC motor-driven oil pump is integral with the main transaxle housing and generates a maximum of 6.8 bar (100 psi) pressure. Oil passages are either machined into the housing or provided by aluminum tubing within the housing. A schematic of the hydraulic system is shown in Figure 4. Dump flow from the pressure control valve is channeled to the various points requiring lubrication and cooling within the transaxle. Three 3-way solenoid valves (normally closed) alternately admit pressurized oil to their respective clutches. No modulation of clutch pressure in response to load demand has been made, as near synchronization is electrically achieved before completion of a shift.

4.5 Battery Selection

Although many new technology battery systems are in development and promise increased range and performance, none are currently available for a cost that could be considered in this near-term system contract. Battery selection was limited to a type available at a cost competitive with current lead-acid types. The AC system testing had been performed with off-the-shelf, deep cycle, 12v marine type batteries. The decision was made to use standard 6v deep cycle batteries of the type used in golf carts. These can be purchased locally at a reasonable price. They do not have the cycle life to be economical over a period of time, but offer reasonable performance while they are relatively new.

A set of 22 Gould (brand name Transcontinental) 6v deep cycle batteries was purchased, 18 for the system plus 4 spares. These batteries were used for motor-controller testing in 1982 and later used in the vehicle for shift tuning and track testing. Only two batteries developed a weak cell necessitating replacement. No other problems have been encountered. These batteries are still in use in the vehicle as of October of 1983 and have required little maintenance. The vehicle actually is driven few miles at a time, and batteries are fully recharged after each use. Total miles on this set of batteries is approximately 350.

5.0 PACKAGING AND FABRICATION

5.1 Motor

The traction motor was fabricated from standard parts and materials as far as possible since it was to be a low cost design. The armature was a lengthened version of a standard production type. The diameter is 5.75" and the stack 6". The armature windings, single-turn formed copper bars, are machine formed and assembled to the commutator. To provide for better commutation in the weak field condition, the standard commutator was replaced with an 83 bar version.

The main field poles are laminated steel with form wound copper coils of 250 turns of 16 gauge wire. There are four poles, 90° apart.

Initially an attempt was made to produce a motor without interpoles. In the weak field condition at high current the commutation became unacceptable and interpoles were added without any size penalty.

The interpoles consist of 11 turns of .2" square wire would on solid iron cores 6" long and ½" thick. There are four interpoles spaced evenly between the main field poles.

To save weight only that portion of the shell supporting the field windings is made of iron; the remainder of the motor shelf is aluminum. The iron ring is a 6" long cylinder with an O.D. of 10.25" and a wall thickness of 11/16". This iron is well into saturation at the maximum field current of 10 amps (2500 AT per pole). Further significant weight reduction would only be possible with less available materials.

The remainder of the motor outer shell is entirely of aluminum. A substantial weight savings is gained without affecting motor performance since the iron is only necessary in the flux path around the field poles.

The length of the motor, with a 10.25" outside diameter, came to 17" long, not counting the output shaft. To this was added a speed pickup at the back end of the motor, increasing the length by approximately 1½" further.

Keeping the overall diameter down reduces the weight but makes it more difficult to achieve the torque and speed characteristics desired. The motor then is a compromise to obtain the best performance in an inexpensive package.

The small diameter means there is minimum space between windings for the required air circulation. To improve air flow a small internal fan was incorporated that alone gives a 16 hp rating for one hour at base speed or above. Under moderate driving conditions there would be no need for further air circulation, saving battery energy. There is an external fan to provide additional air if the motor exceeds a pre-set temperature.

The motor mates to the transaxle by means of a recess on the face surrounding the output shaft; an "O" ring gasket seals the connection. The motor is supported by the transaxle where it mates and by a bracket at the rear.

Electrical connections to the motor are made with six 5/16" diameter brass bolts, around the circumference near the rear end, two bolts for the main field, two for the armature and two for the series interpoles. In a production style motor the connection could be in a junction box to protect them from contamination.

The speed pickup on the rear of the motor is a toothed wheel and magnetic sensor. Thirty teeth on the wheel which are adequate since motor speed is only monitored above 1800 rpm base speed.

There are two temperature sensors on the motor monitoring field assembly temperature. One is a standard IC engine water temperature sensor connected to the existing temperature gauge on the instrument panel. Motor operating temperatures are not much different than the normal water temperature in an IC engine vehicle; this gives the driver some indication if the motor is overheating. The second temperature sensor is a solid state type connected to the logic in the vehicle interface box. This sensor will activate the external cooling fan for the motor if the temperature exceeds 180^{o}F.

5.2 Controller

The controller was to be installed under the hood to provide accessibility since it was a first generation prototype. Based on previous experience, the unit was divided into three basic sections for packaging that would allow testing and modifications to be made independently on each. One package would contain the power contactors, the second would contain the DC-to-DC converter and bus capacitors and the third the logic and chopper.

The space available under the hood allowed for a total size of 15½" wide, 16½" deep and up to 12" high, approximately 1.8 cu. ft.

A section of finned heat sink was obtained having a thermal coefficient and mass sufficient to cool the main chopping transistor on an almost continuous basis at full load. This is not necessary in practice due to the limited time spent chopping high currents, but for a prototype controller it meant there would be no restrictions on operating level or time during development or testing.

The logic package was built around the heatsink and measures 15¼ x 6 x 9" high. The power chopper, free wheeling armature diode, and snubber components are mounted directly to the heatsink.

In a pocket at the end of the heatsink there are three P.C. boards. The first contains the power supply regulators and the F.E.T. driver for the main chopping transistor. The second board contains the microprocessor and logic for the speed pickups and gear selector inputs and the output drivers for the transaxle control solenoids. The third board has all the logic for control of the main chopper.

The second section contains two main bus capacitors and the DC-to-DC converter that charges the 12v auxiliary battery while driving and provides isolated power for the controller logic. This section is 15¼ x 4½ x 9" high.

The third contactor section contains two large power contactors, one for controlling the main input power from the traction battery pack and the other for performing the crossover switch for armature to field control. It also contains a smaller relay to reverse the polarity of the motor field to provide a reverse gear for backing up the vehicle and a parallel relay that activates the backup lights. Since the main power comes into the controller through this section the current sense module for armature current sensing is also in this box. This section is 15¼ x 6½ x 9".

The entire controller is assembled into one package 15¼ x 17 x 9". On top, connecting the first and third sections, are four copper bus bars. These connect the motor and crossover contactor from the third section to the free wheeling diode and main chopping transistor in the first section. The main traction battery connector is on top of the third section and is connected to the bus capacitors in the second section by means of short copper straps.

The 12v auxiliary battery plugs into the second section on top. There are two cables from the first (logic) section to the third (contactor) section. One for the armature current sensor feedback to the logic, and the other to provide power to the contactor coils.

On top of the logic section are six connectors selected so that they are noninterchangeable. At the rear, nearest the vehicle firewall is the four-pin connector from the motor and ground speed pickups. Next a four-pin connector outputs signals to the vehicle interface box to interrupt power in case of an electrical failure. Third is an eight-pin connector from the gear selector. Fourth is a three-pin connector from the second section (DC-to-DC converter) providing isolated 12v and 7v for small signal logic and chopper base drive power. Last is a six-pin connector from the throttle and service brake pedals for speed and brake demands. Next to this row of connectors is a single five-pin connector to the transaxle which powers the solenoid valves that apply the clutches.

A single additional lead enters the top of the second section (DC-to-DC converter) from the vehicle 12v system. When the vehicle is started by means of the ignition key switch, the converter is started to power the logic and change the 12v battery.

5.3 Transaxle

The main objective of transaxle packaging was to make the two- and three-speed versions as compatible as possible for vehicle installation and motor mating.

This way the propulsion systems would be nearly interchangeable from one vehicle to another. Common mounting hardware and mounting points in the vehicle could be shared. Output shafts and universal joints were identical for both units. The front mount in the vehicle did have to be modified slightly because the motor was larger and the mounting bracket was moved forward one inch. No change was made that would preclude the use of the AC system in this vehicle if that became necessary.

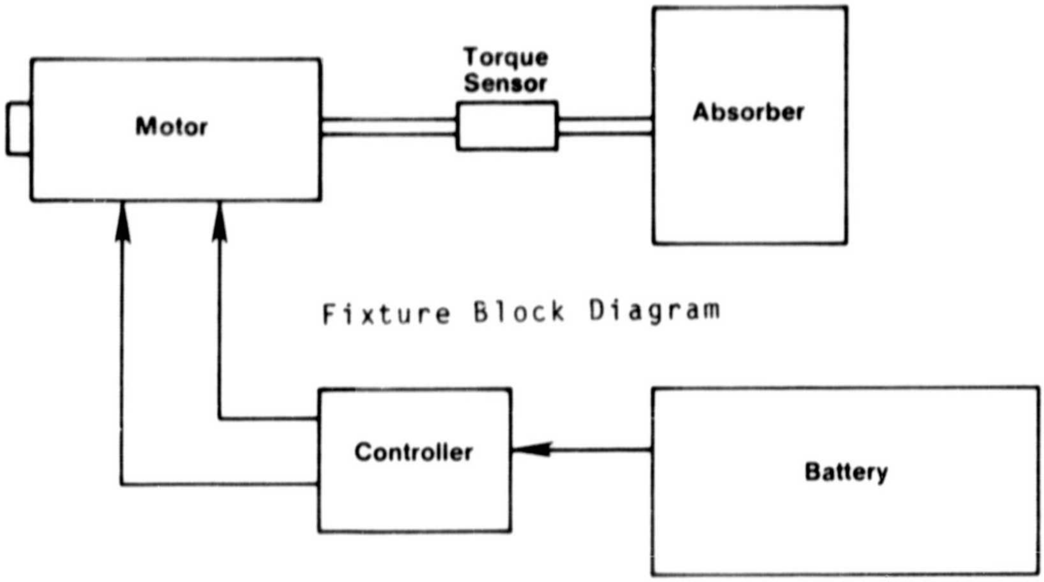
As in the two-speed version, many of the components were taken from existing production transmissions. To save time and cost, gears, splines and shafts were modified, if necessary, or removed from their original parts and reassembled to form new assemblies by means of an electron beam welder. This welder proved invaluable for this task because of the ability to weld previously hardened parts, even to unhardened ones. Extensive use was made of this technique.

6.0 COMPONENT TESTING

Contract DEN 3-258 required performance testing of the individual propulsion system components. The motor and controller were tested together on an absorbing dynamometer, and then together data taken to permit individual efficiencies to be determined. The transaxle was tested on an absorbing dynamometer which permitted testing over its full speed and torque operating range. A combined test on a dynamometer was not carried out. Combined efficiency was calculated from the previous two results.

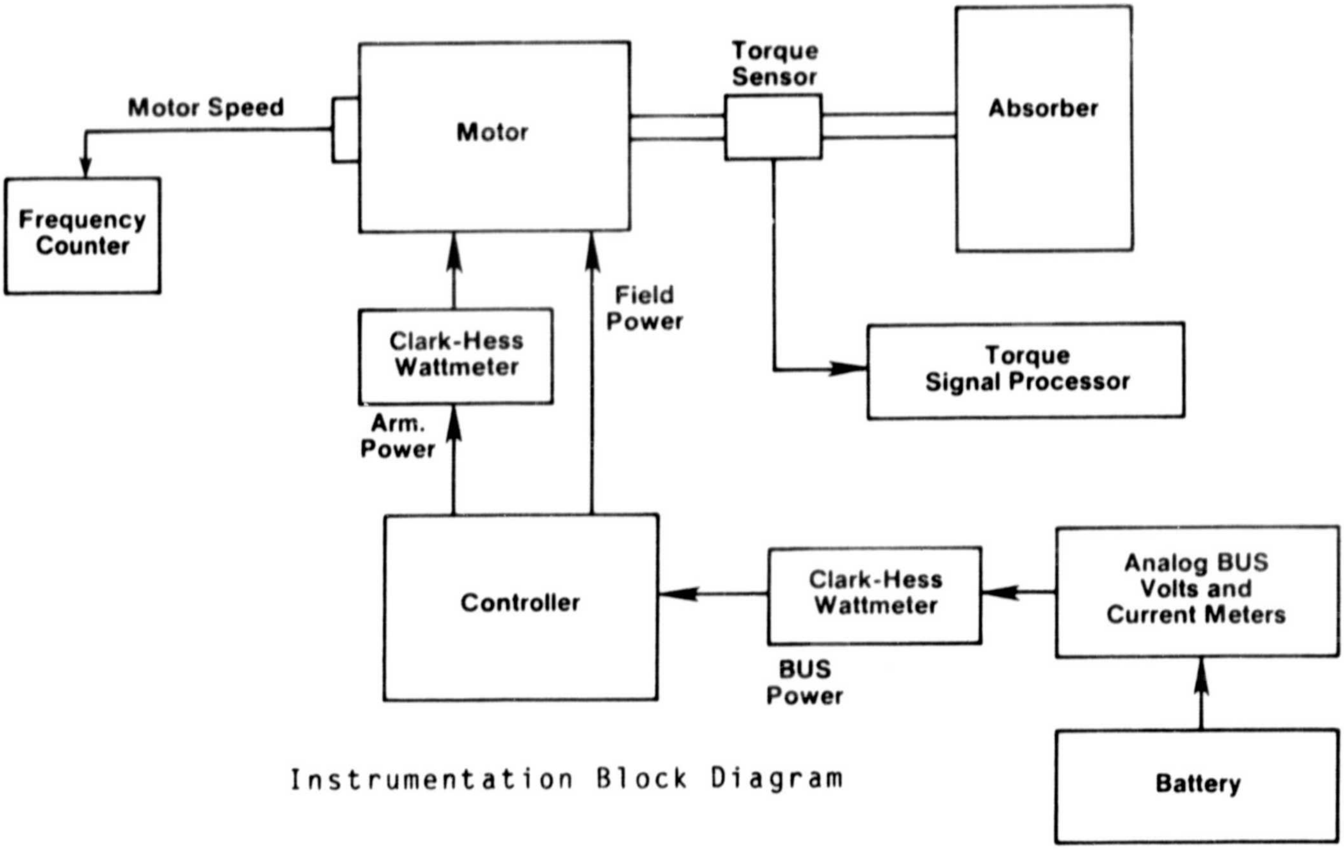
6.1 Motor-Controller Testing

6.1.1 Test Fixture



Fixture Block Diagram

6.1.2 Test Instrumentation and Accuracy



Instrumentation Block Diagram

When initial test data taken at ERC was reduced and compared to the original motor data from the manufacturer, it became apparent that an error existed in instrumentation causing efficiency numbers to be unusually high. The motor and controller together appeared to be above 90% efficient which for a DC brush commutated machine is not likely.

Investigation showed an error had been made when calibrating the amplifier of the torque transducer used to measure motor output. The error gave readings 4% high.

To measure input power from the batteries and into the motor armature two Clark-Hess wattmeters and coaxial shunts were used. These instruments are not as accurate measuring DC power as AC. To verify calibration a direct comparison was made with DC volts and current measured in parallel. The Clark-Hess meters are specified to be better than 1%: one read 1% low and the other 3% low. The 1% error was in the armature power circuit and the 3% on the bus input power. Fortunately the readings are repeatable and the error appears constant as a percentage of the power reading. Several tests runs were made with the motor alone and the Clark-Hess meters in parallel with bus voltage and current meters to verify repeatable readings and consistent error. These readings verified the error to be constant and therefore could be applied to the original data to provide corrected efficiencies which compare very closely (within 1%) to the data supplied by the motor manufacturing Eaton Division.

6.1.3 Motor Test Results

See Table 1. Below the 1800 rpm base speed, ERC data gives a lower efficiency than the manufacturer. This is due to ERC testing with a chopper driving the armature while the manufacturer utilized a variable DC source.

TABLE 1
ARMATURE EFFICIENCY
ERC vs. MANUFACTURER'S DATA

ERC Per Unit Torque 1 = 60 lb/ft @ 1800 RPM

RPM	.1	.25	.50	.75	1	1.25	1.50	Per Unit Torque
600			80	76	75			
1200		83	85	83	82			
1800		83	89	88	89	73		E R C
2000	59	80	88	88	85	74		D A T A
2400	67	80	87	90	86	78		
3000	67	82	88	87	85	81	73	
3600	60		86	87	85	78	70	

Manuf.

RPM		.25	.50	.75	1			Per Unit Torque
600		81	87	84	79			
1200		82	86	87	85			
1800		83	87	87	87			F A C T O R Y
2000			86	87	85	82		D A T A
2400			85	87	86	82		
3000			86		84	80		
3600			85	85	84	78		

The following graph, Figure 6.1.3-1, shows ERC data and the manufacturer's data for 1.0 per unit torque versus speed.

Figure 6.1.3-2 shows motor efficiency versus per-unit torque load as a function of motor speed. Efficiency is at a peak for the 0.5 to 1.0 per-unit torque operating level throughout the speed range. At very light or very heavy loads the efficiency will drop significantly. This shows the motor is optimized for maximum cruising efficiency, not acceleration.

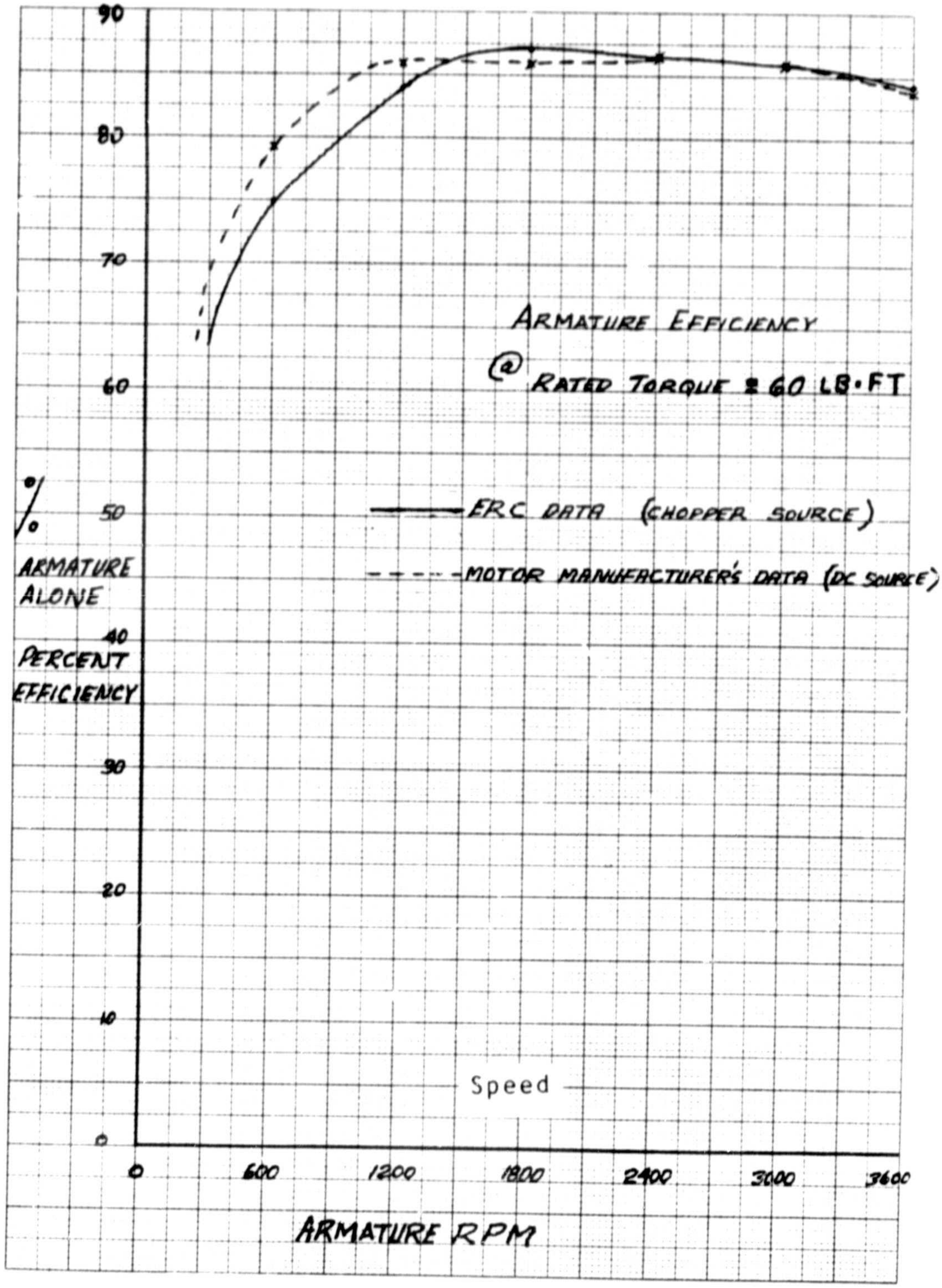

ARMATURE EFFICIENCY
@ RATED TORQUE ≈ 60 LB•FT
ERC DATA (CHOPPER SOURCE)
MOTOR MANUFACTURER'S DATA (DC SOURCE)
% ARMATURE ALONE
PERCENT EFFICIENCY
90
80
70
60
50
40
30
20
10
0
Speed
0
600
1200
1800
2400
3000
3600
ARMATURE RPM

Figure 6.1.3-1

Motor efficiency at various per unit torque loads.

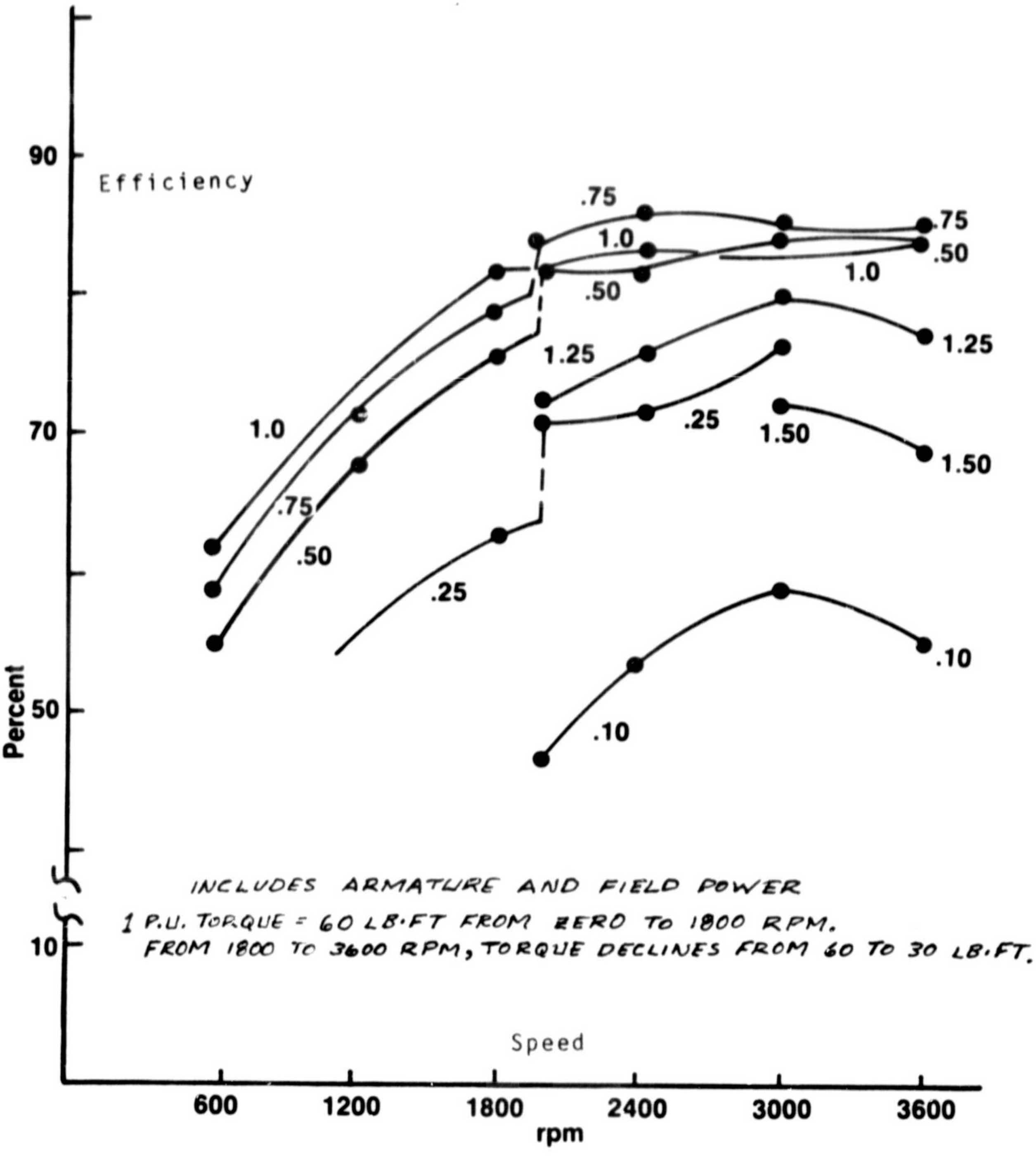


Figure 6.1.3-2

6.1.4 Motor-Controller Test Results

After obtaining motor efficiency alone, the controller efficiency was included. The following graphs show motor-controller efficiency as a function of motor load at constant speed. Efficiency of the motor and controller together can be determined for steady speeds or maximum acceleration by dividing the vehicle road load lb-ft by the transaxle ratio and efficiency. The resulting lb-ft load for a particular motor speed gives the efficiency. Following are five graphs, Figures 6.1.4-1 to 6.1.4-5, with motor speeds from 1200 to 3600 rpm. On these graphs the road load for steady speed operation is marked. Since the transaxle has three speeds, there is more than one operating point for each motor speed above base speed, 1800 rpm.

The controller is designed to be operated primarily in the field weakening mode where power dissipation is quite small. When in the armature chop mode, however, the motor field is coupled directly to the bus and dissipation in the field is high. Also, if vehicle is on a steep grade, the armature chopper will be handling high power and losses will be significant. To establish whether the thermal capacity of the motor and controller were adequate during sustained armature chopping, the following test was run.

The motor and controller were fitted with seven thermocouples to monitor temperature rise. Test conditions were

1. chopper at 50% duty cycle
2. current at limit, approximately 160 amps
3. motor at 900 rpm
4. motor torque at 60 lb-ft
5. motor field tied to 108v bus

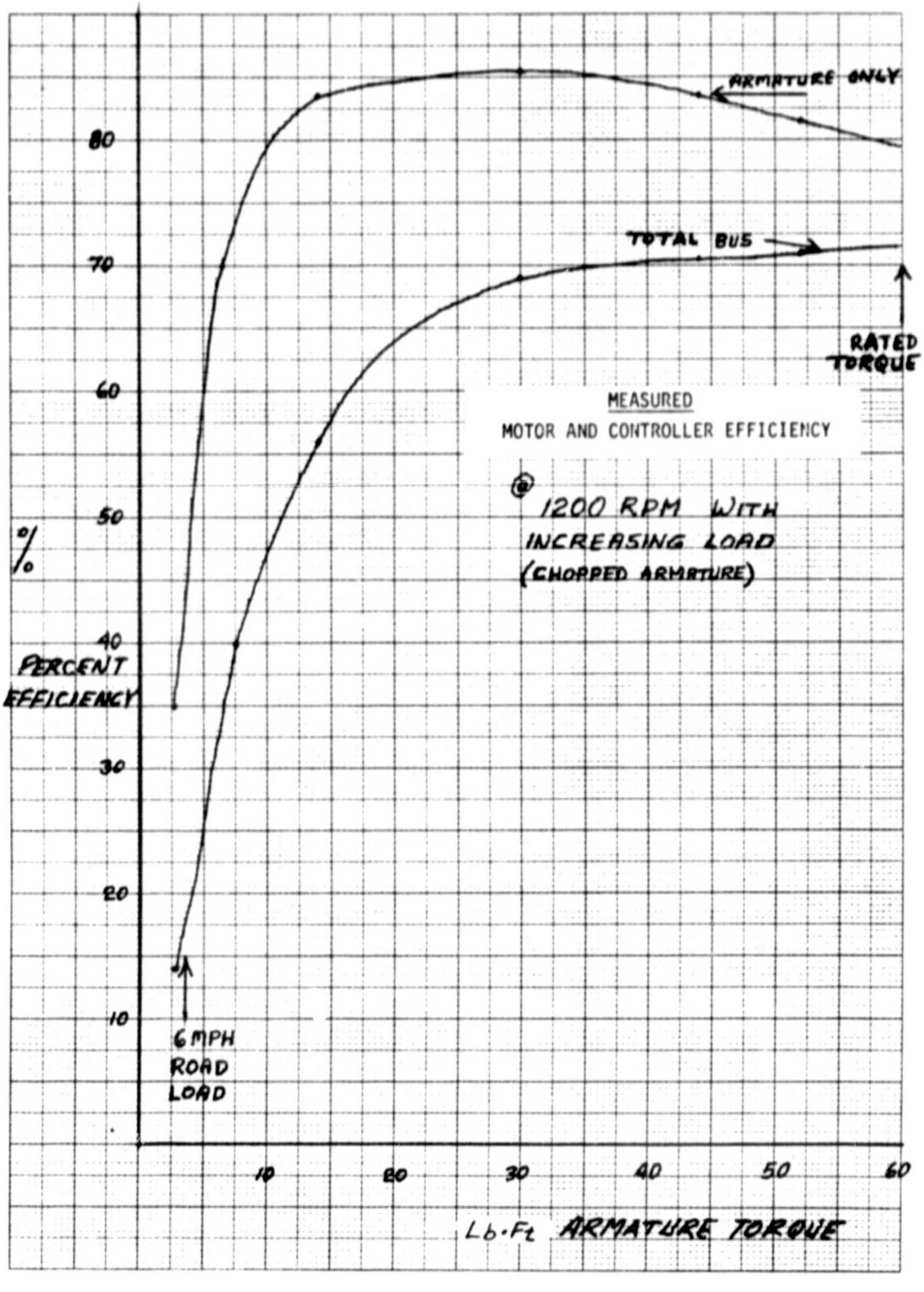

ARMATURE ONLY
TOTAL BUS
RATED TORQUE
MEASURED
MOTOR AND CONTROLLER EFFICIENCY
@ 1200 RPM WITH
INCREASING LOAD
(CHOPPED ARMATURE)
%
PERCENT EFFICIENCY
80
70
60
50
40
30
20
10
6 MPH
ROAD
LOAD
10
20
30
40
50
60
Lb·Ft ARMATURE TORQUE

Figure 6.1.4-1

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OF POOR QUALITY

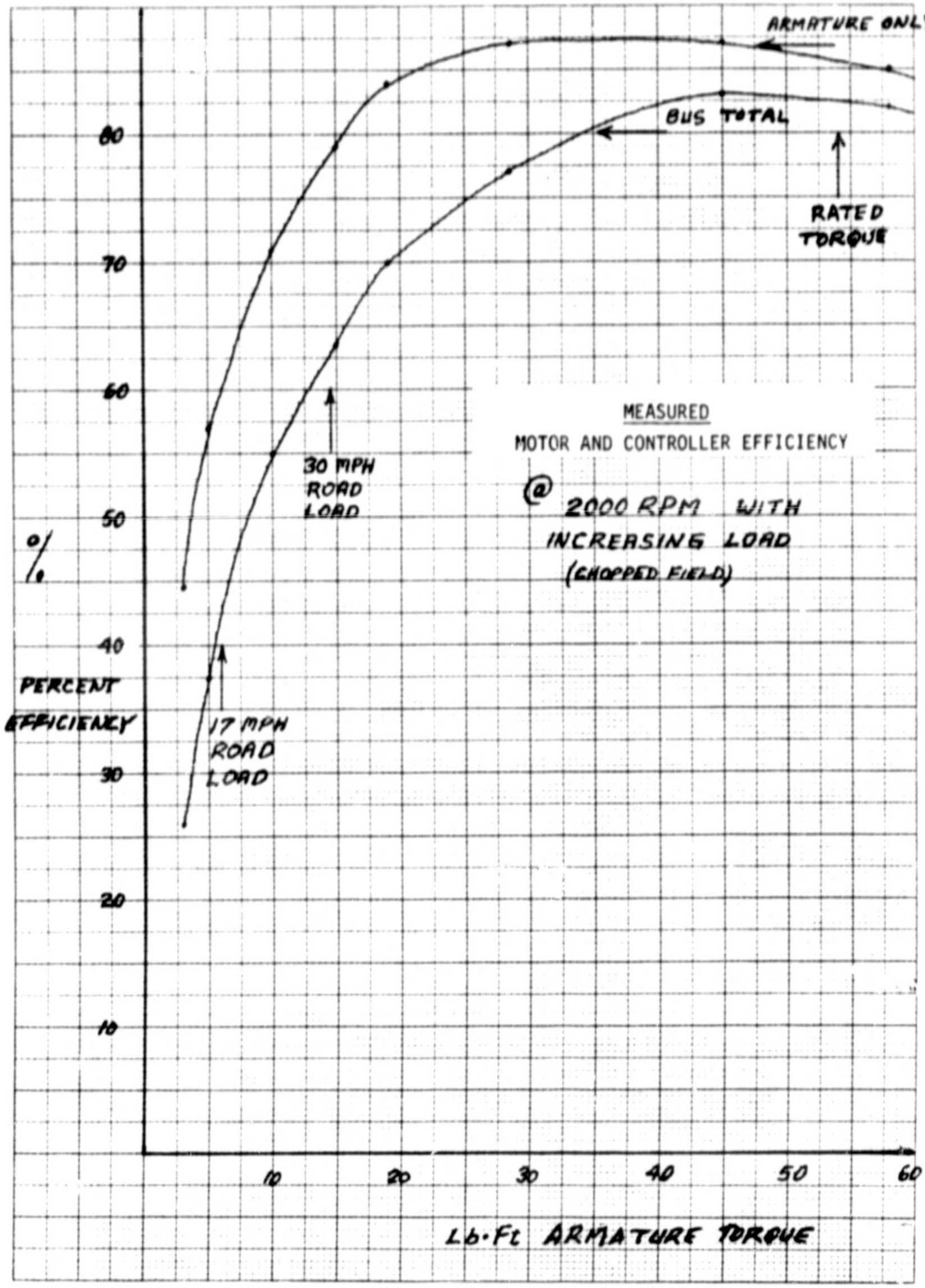

Figure 6.1.4-2

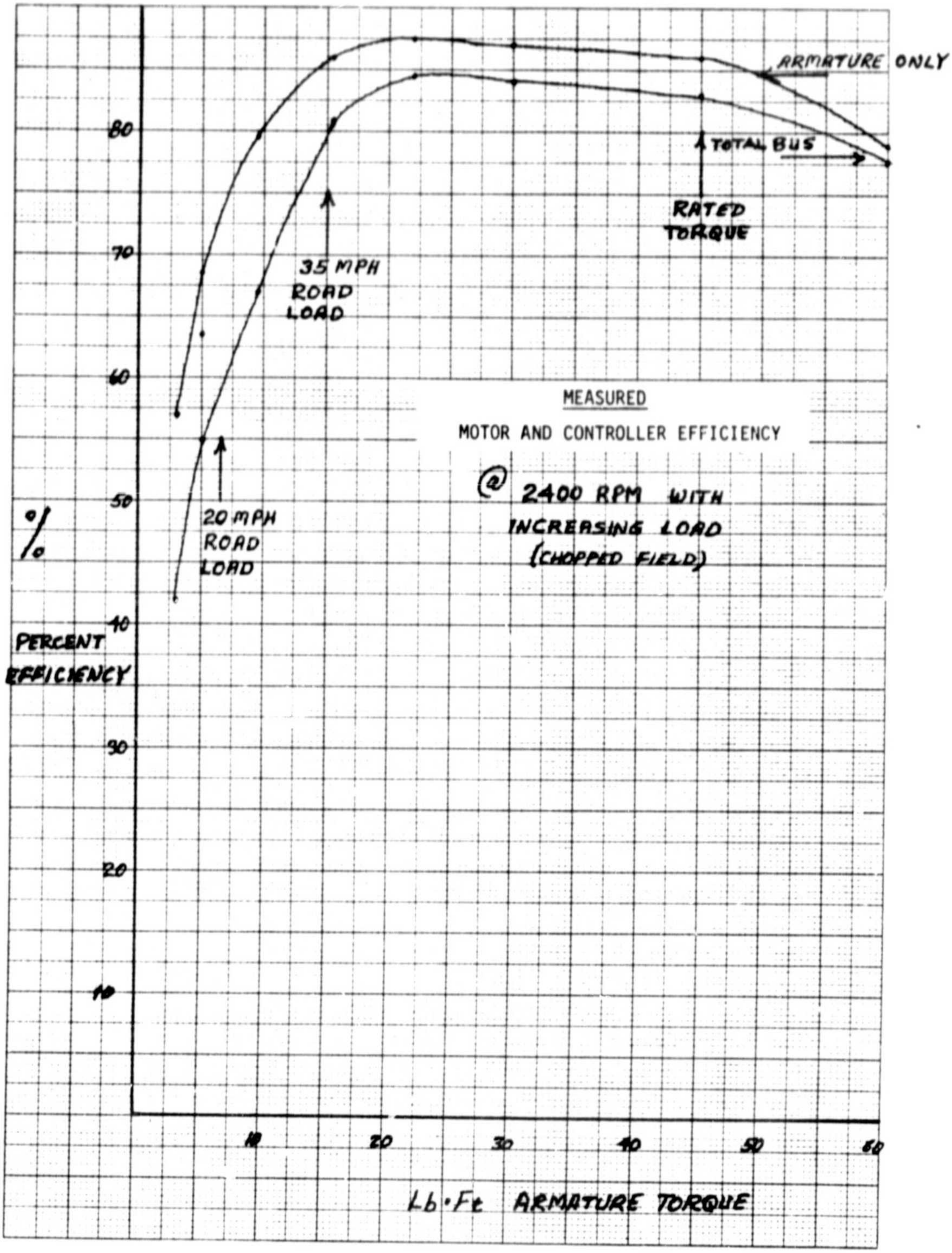
ARMATURE ONLY
TOTAL BUS
RATED TORQUE
35 MPH ROAD LOAD
20 MPH ROAD LOAD
MEASURED
MOTOR AND CONTROLLER EFFICIENCY
@ 2400 RPM WITH INCREASING LOAD (CHOPPED FIELD)
%
PERCENT EFFICIENCY
10
20
30
40
50
60
70
80
Lb·Ft ARMATURE TORQUE

Figure 6.1.4-3

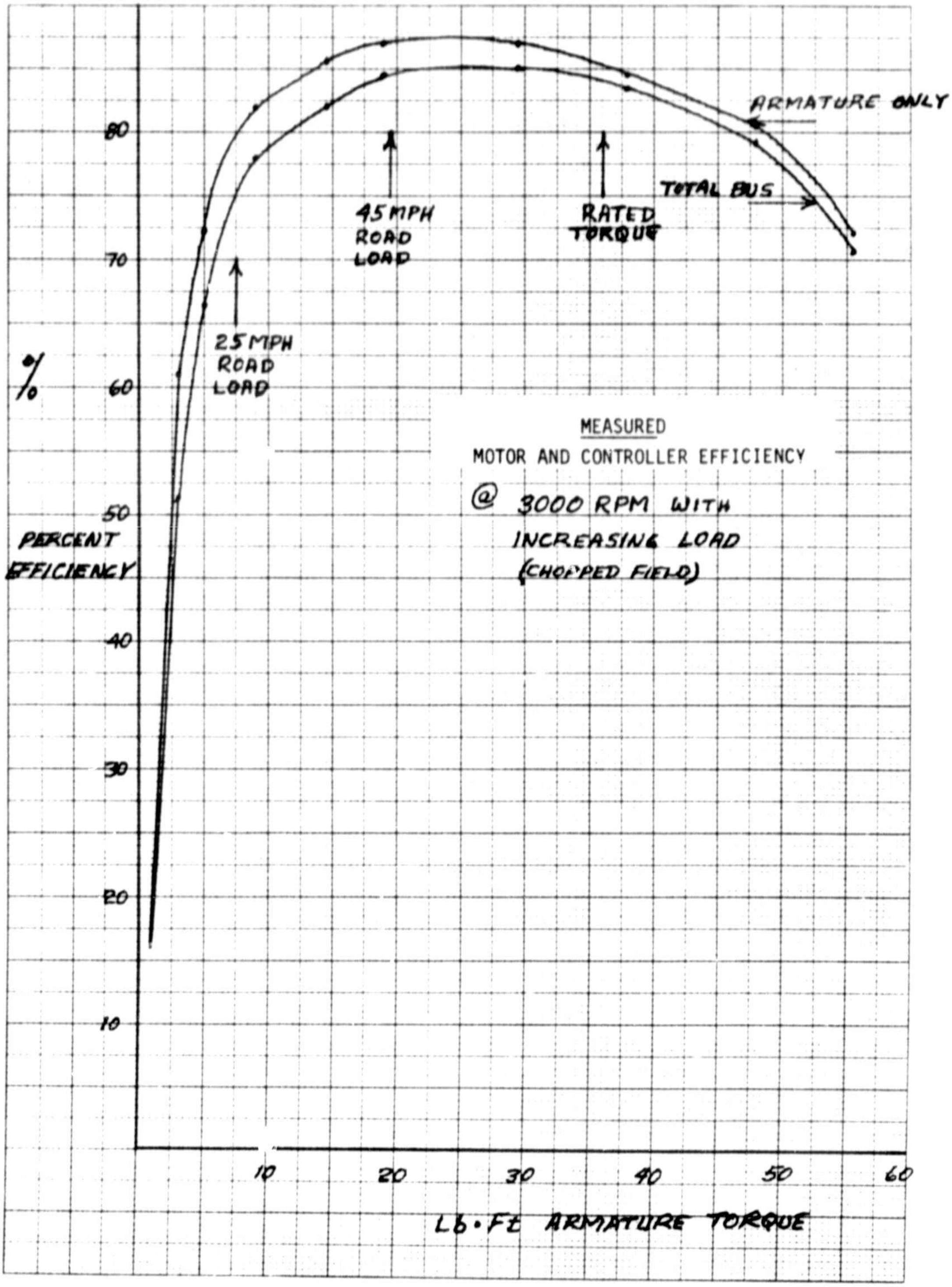
ARMATURE ONLY
TOTAL BUS
45 MPH
ROAD
LOAD
RATED
TORQUE
25 MPH
ROAD
LOAD
%
PERCENT
EFFICIENCY
MEASURED
MOTOR AND CONTROLLER EFFICIENCY
@ 3000 RPM WITH
INCREASING LOAD
(CHOPPED FIELD)
80
70
60
50
40
30
20
10
10
20
30
40
50
60
Lb·Ft ARMATURE TORQUE

Figure 6.1.4-4

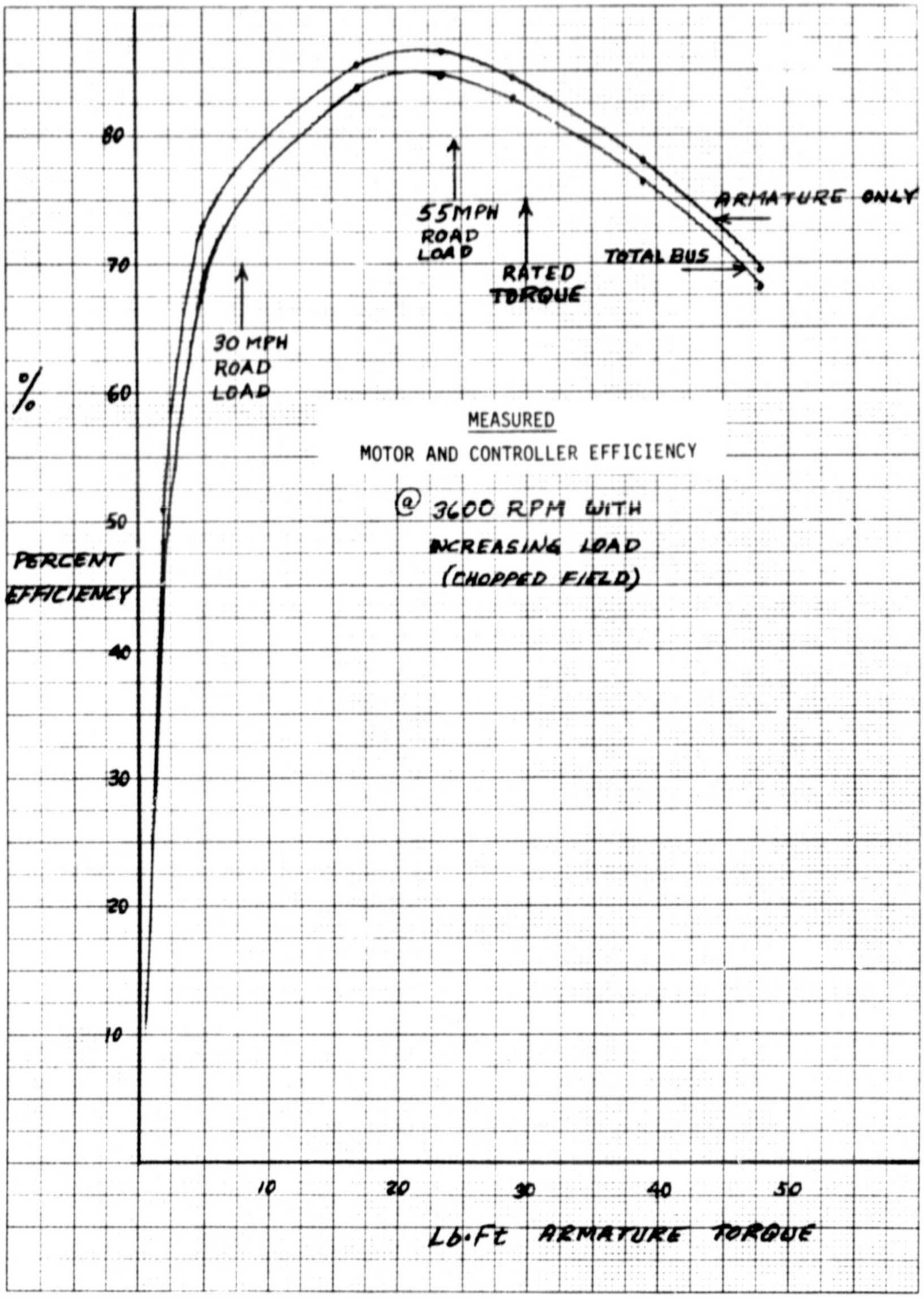
MEASURED
MOTOR AND CONTROLLER EFFICIENCY
@ 3600 RPM WITH
INCREASING LOAD
(CHOPPED FIELD)
ARMATURE ONLY
TOTAL BUS
55 MPH
ROAD
LOAD
RATED
TORQUE
30 MPH
ROAD
LOAD
%
PERCENT
EFFICIENCY
80
70
60
50
40
30
20
10
10
20
30
40
50
Lb·Ft ARMATURE TORQUE

Figure 6.1.4-5

The test ran 10 minutes under these conditions. This is considered more extreme than foreseeable operating conditions on the road. In actual operation at low speeds, the main contactor will drop out in the armature chop mode if the vehicle is coasting. This test is only applicable to hill climbing. Data from this test is shown in Table 2.

TABLE 2

Time (Minutes)	**Temperature °F Thermocouple No.**						
	1	2	3	4	5	6	7
0	74	74	74	74	74	74	74
1	94	126	75	78	100	76	75
2	107	157	76	83	119	78	76
3	114	170	78	89	138	80	76
4	123	175	79	94	153	83	77
5	128	181	80	98	165	84	78
6	133	186	82	102	179	89	78
7	139	188	84	106	190	92	79
8	142	193	86	109	199	96	80
9	146	198	87	113	210	100	81
10	150	199	89	116	219	105	82

Test points for thermocouples:

1. Freewheeling diode on main heatsink
2. Chopping transistor on main heatsink
3. Auxiliary bus capacitor for chopping transistor
4. Snubber diode on main chopping transistor
5. Motor field winding (internal)
6. Motor shell (external)
7. Main bus capacitors

This data is plotted in graph form in Figure 6.1.4-6. Note, except for the field winding, that all other points appear to be close to stabilizing. During this test the controller was sitting on top of a bench with no air flow over the fins of the heatsink. With some air flow, heatsink temperatures would be leveling off.

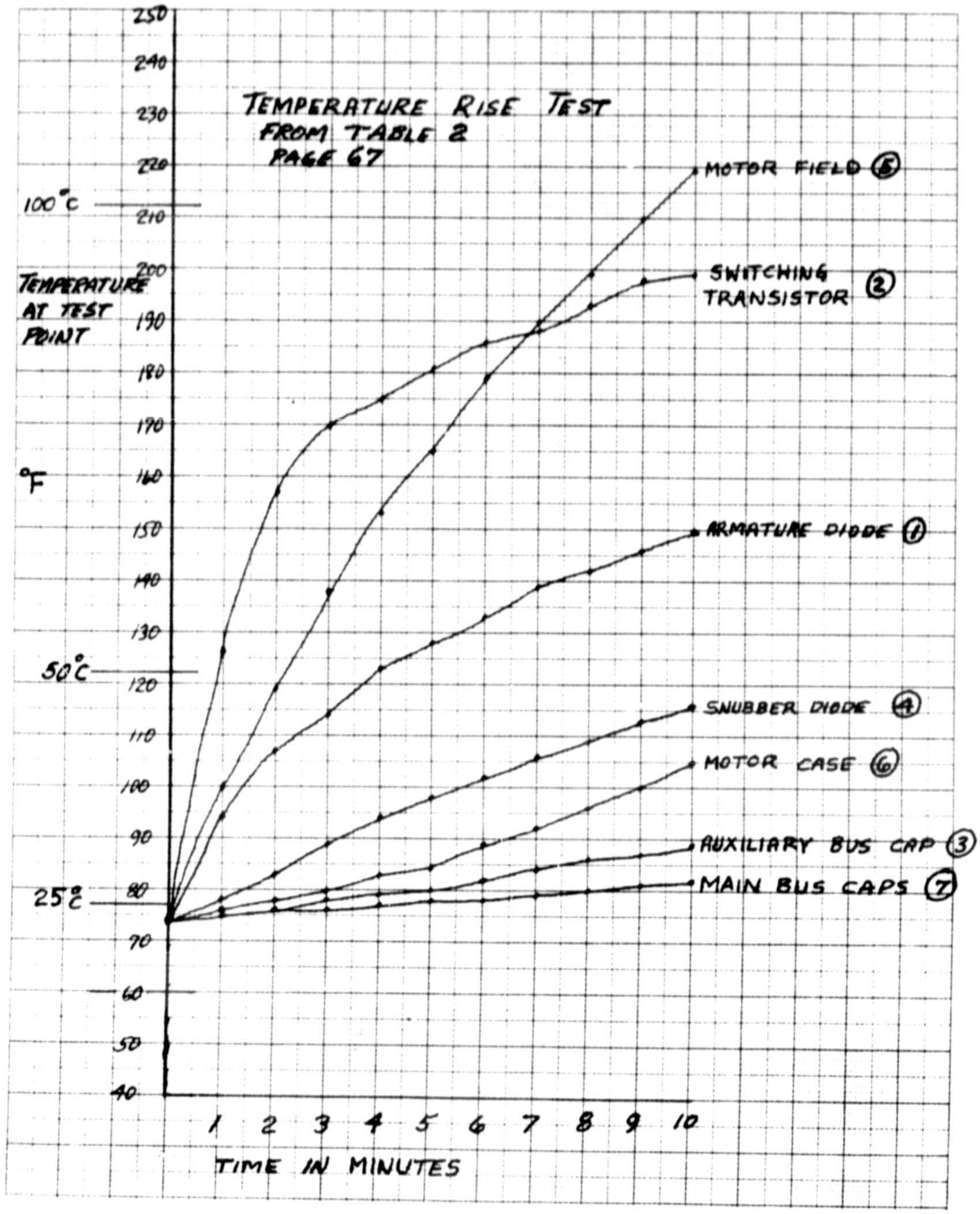
TEMPERATURE RISE TEST
FROM TABLE 2
PAGE 67
MOTOR FIELD ⑤
SWITCHING TRANSISTOR ②
ARMATURE DIODE ①
SNUBBER DIODE ④
MOTOR CASE ⑥
AUXILIARY BUS CAP ③
MAIN BUS CAPS ⑦
TEMPERATURE AT TEST POINT
°F
100°C
50°C
25°C
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
1 2 3 4 5 6 7 8 9 10
TIME IN MINUTES

Figure 6.1.4-6

6.1.5 Predicted Motor-Controller Efficiency in the Vehicle

Figure 6.1.5-3 is a graph of vehicle road load versus speed. This is calculated data based on known vehicle parameters. Table 3 shows load versus speed at 5 mph increments. Note that air drag and tire drag are nearly equal at 55 mph.

W = Vehicle Weight		3900 lbs. (GVW)
A = Frontal Area		19 sq. ft.
D = Drag Coefficient		0.40

Air drag is calculated from the following equation:

$$F_D = 2.151\ K_1\ A\ D\ V^2$$

K_1 = Air Constant, 1.19×10^{-3}

V = Vehicle Speed

Rolling resistance of tires is calculated from the following equation:

$$F_R = K_2\ W(1 + 2.05 \times 10^{-3}\ V + 2.58 \times 10^{-5}\ V^2)$$

K_2 = Tire Resistance, 0.12 lbs/lb

Combining these equations gives

$$F_T = 46.8 + 0.0959\ V + 0.0207\ V^2 \text{ lbs.}$$

By inserting the vehicle speed, the road load value can be determined at any point.

By using the data in Figures 6.1.4-1 to 6.1.4-5, the graphs in Figures 6.1.5-1 and 6.1.5-2 were generated--first, the efficiency of the motor and controller at steady speed road loads, and then at maximum acceleration. Note that shift points are assumed to be at 17 and 31 mph.

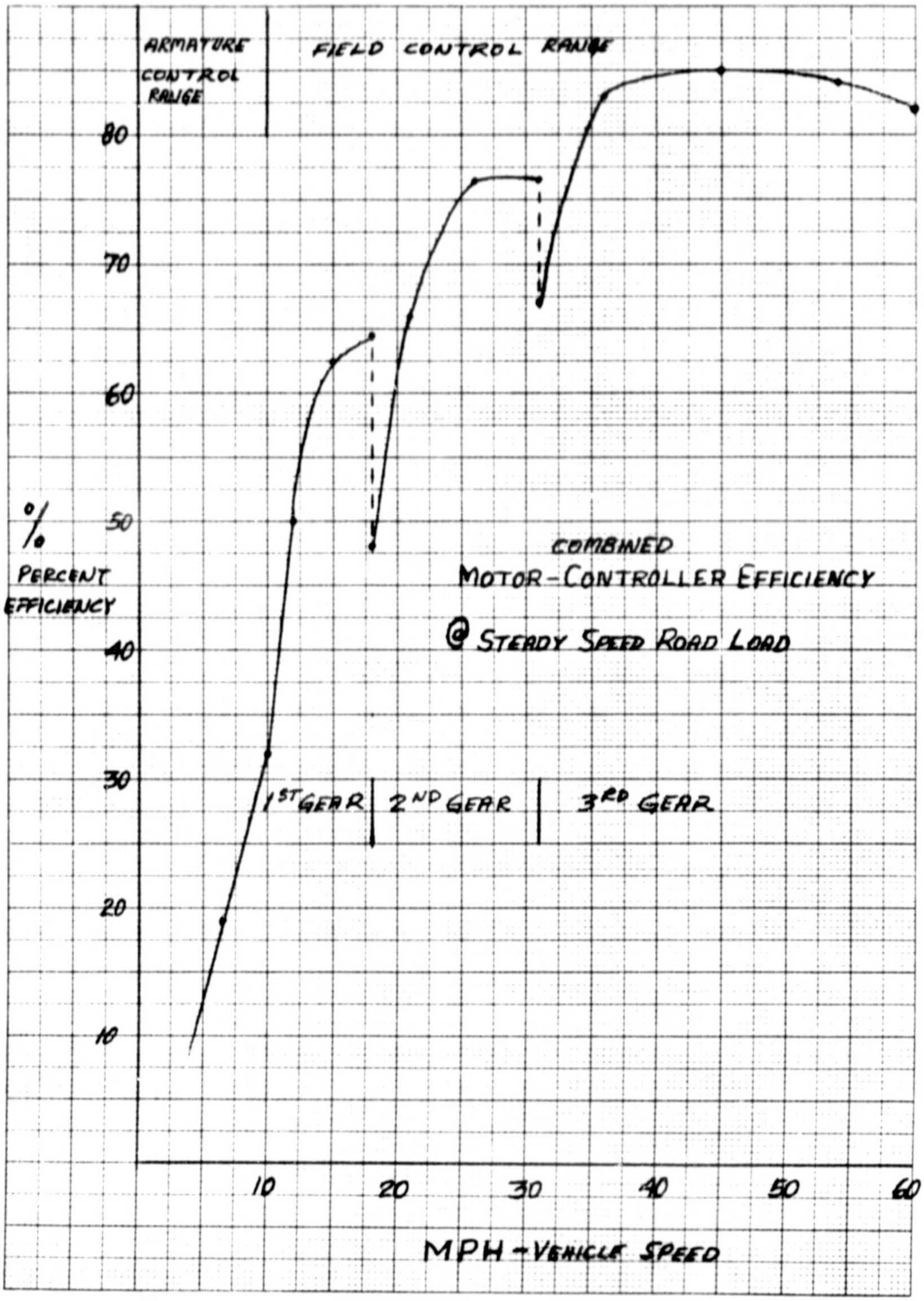
ARMATURE CONTROL RANGE
FIELD CONTROL RANGE
80
70
60
%
PERCENT EFFICIENCY
50
40
30
20
10
COMBINED
MOTOR-CONTROLLER EFFICIENCY
@ STEADY SPEED ROAD LOAD
1ST GEAR
2ND GEAR
3RD GEAR
10
20
30
40
50
60
MPH - VEHICLE SPEED

Figure 6.1.5-1

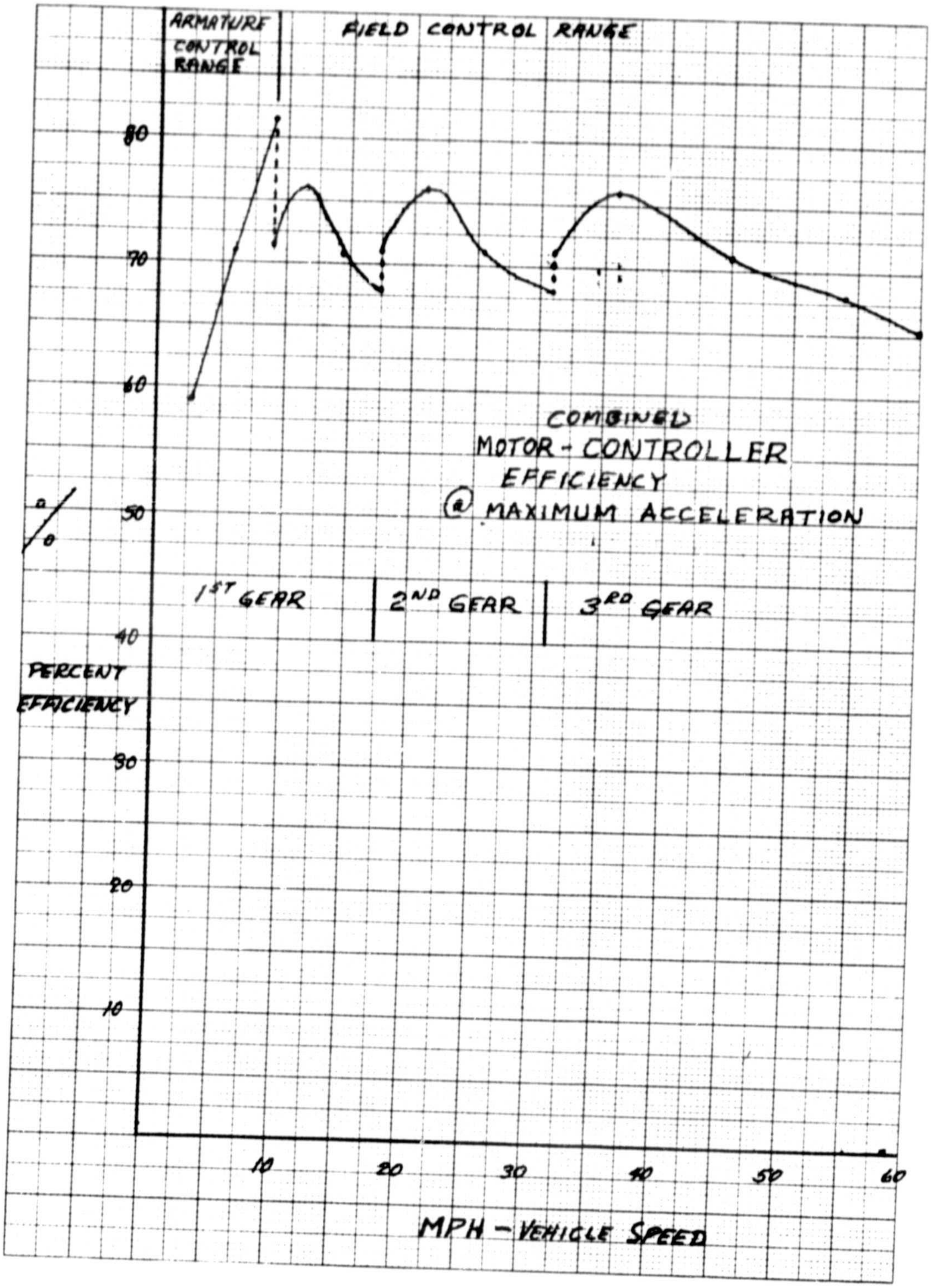
ARMATURE CONTROL RANGE
FIELD CONTROL RANGE
COMBINED
MOTOR-CONTROLLER
EFFICIENCY
@ MAXIMUM ACCELERATION
1ST GEAR
2ND GEAR
3RD GEAR
PERCENT EFFICIENCY
%
80
70
60
50
40
30
20
10
10
20
30
40
50
60
MPH — VEHICLE SPEED

Figure 6.1.5-2

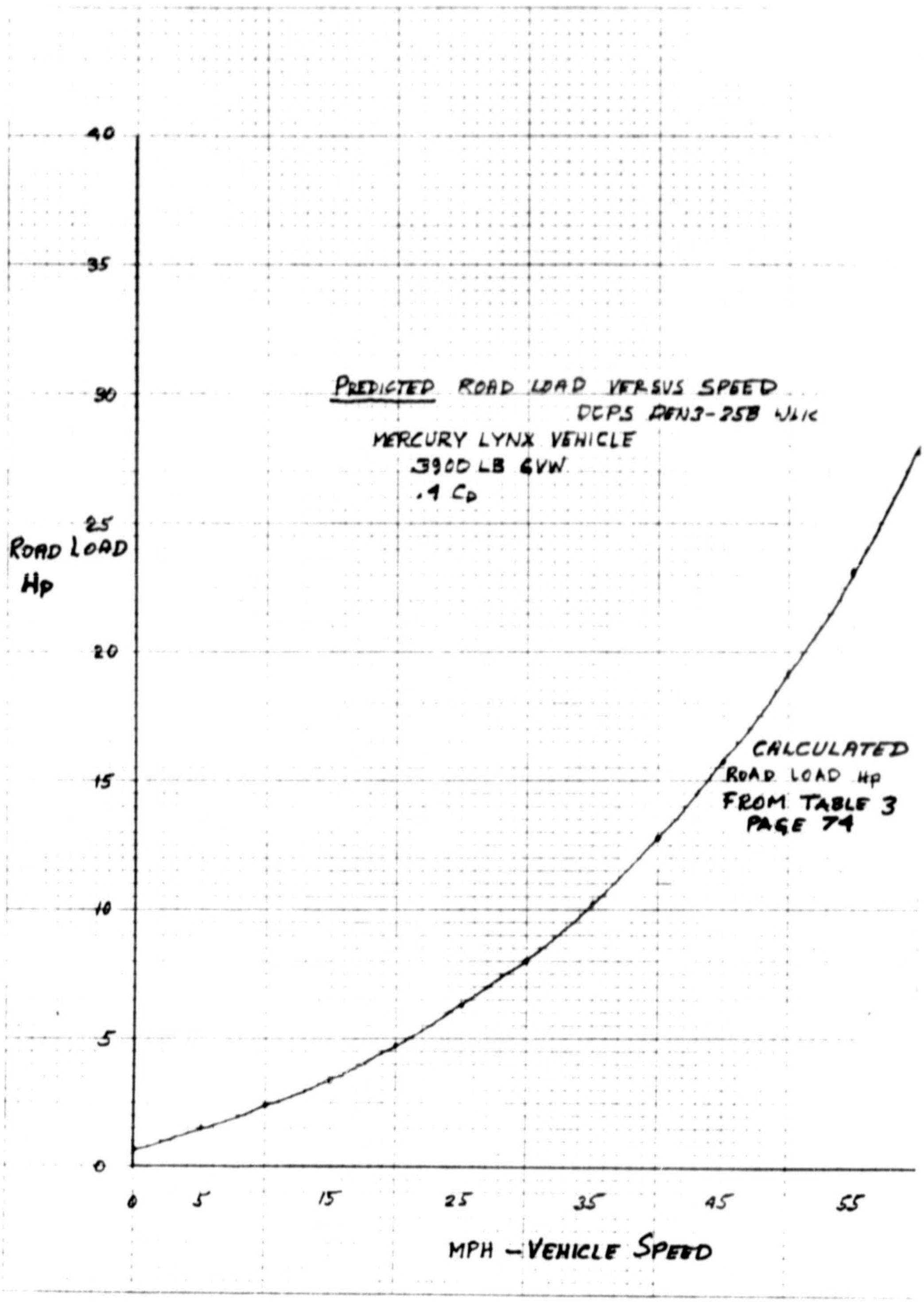
PREDICTED ROAD LOAD VERSUS SPEED
DCPS DEN3-25B
MERCURY LYNX VEHICLE
3900 LB GVW
.4 C_D
ROAD LOAD Hp
CALCULATED ROAD LOAD Hp FROM TABLE 3 PAGE 74
MPH – VEHICLE SPEED
0
5
10
15
20
25
30
35
40
45
55

Figure 6.1.5-3

TABLE 3

MPH	Air Drag	Tire Drag	Total
0		46.8	
5	0.49	47.3	47.8
10	1.95	47.9	49.8
15	4.38	48.5	52.9
20	7.78	49.2	57.0
25	12.16	49.95	62.1
30	17.51	50.8	68.3
35	23.83	51.6	75.5
40	31.13	52.6	83.7
45	39.39	53.6	92.9
50	48.63	54.6	103.2
55	58.85	55.7	114.6
60	70.03	56.9	126.9
65	82.19	58.1	140.3
70	95.32	59.4	154.7

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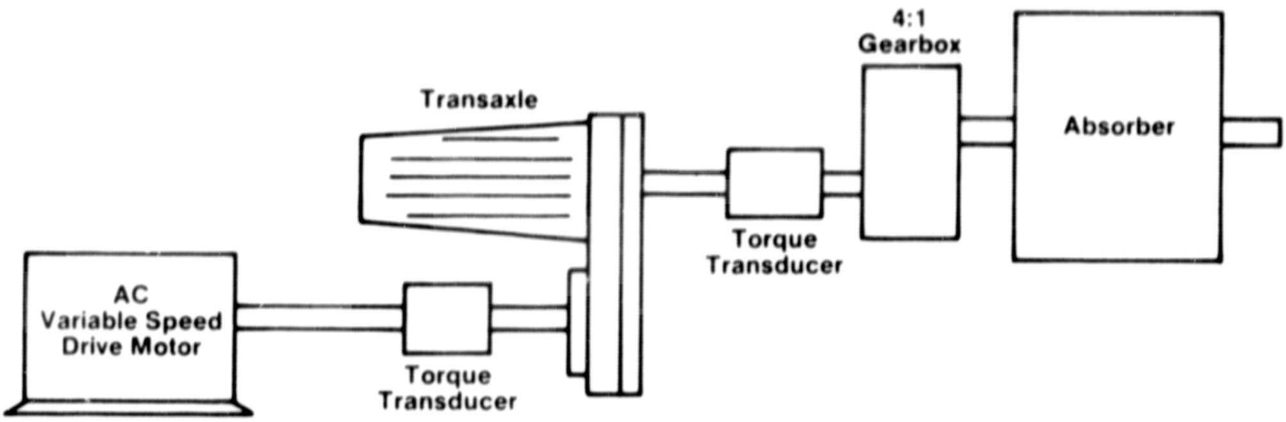
6.2 Transaxle Development and Testing

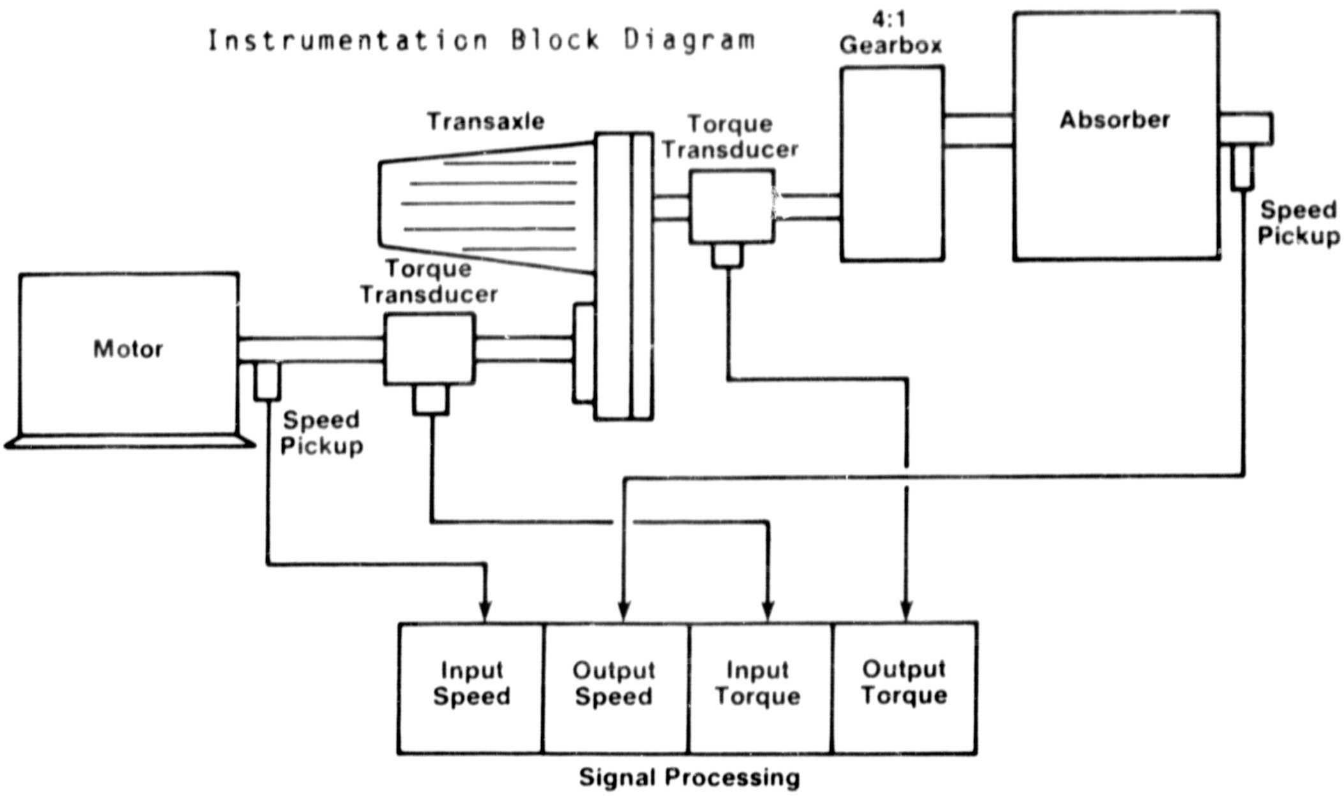
6.2.1 Test Fixture



Fixture Block Diagram

6.2.2 Test Instrumentation

Instrumentation Block Diagram



6.2.3 Problem Areas on Test

Mechanically the transaxle performed correctly, providing three distinct ratios with the correct ratio change for each gearshift. Efficiency in each gear was acceptable, high eighties in first and second gear and low nineties in third gear. A lubrication problem developed at high input RPM. Many changes were made to provide more oil to the final reduction planetary which was the only component failing under high speed testing. A brief summary of each teardown of the transaxle during testing follows.

<u>12-7-82 - 1st run</u>
Failed final planetary completely.

Sleeve bearings on low clutch piston and second gear housing seized to shaft, broke differential locking parts.

a. Grooved all bronze sleeve bearings for better lube.
b. Added oil holes to many shafts to improve circulation.
c. Added drain holes to improve oil drainage.

<u>12-17-82 - 2nd run</u>
Plastic thrust washer on 3rd gear broken (during assembly).

Failed final planetary and thrust bearing (thrust bearing due to lack of travel clearance of high gear clutch).

a. Parts modified to provide clearance.

<u>1-20-83 - 3rd run</u>
Hot spot at second gear clutch.
Second gear ring gear assembly hitting housing.

<u>1-26-83 - 4th run</u>

Some vapor at loaded condition disappeared when load was removed.

<u>1-27-83 - 5th run</u>

Ran for NASA and torn down. Achieved efficiency objectives.

1. Sun gear with bronze bushing heating.
2. Thrust bearing opposite also heating.
3. Needle bearing in case by third clutch heating.
    a. All planetary carriers modified to improve oiling.
    b. Radial grooves added to solid thrust washers.
    c. Additional holes for better oiling.
    d. Additional holes for better draining.

<u>2-1-83 - 6th run</u>

Vapor in high gear at high load.

Failed final planetary, apparent lack of oil.

a. Added vespel oil dam in third gear set to reduce oil flowby.
b. Reduced radial grooves in vespel thrust washer for same reason.
c. Rebuilt final planetary again and modified with oil groove.

<u>2-7-83 - 7th run</u>

Sixty minutes in third gear and again vapor.

Overheated final planetary.

a. All planetary sets rebuilt and modified sun gear pins with grooves to permit better lubrication.

<u>2-10-83 - 8th run</u>

Still vapor at high load and speed third gear.

a. Began reducing some oil holes to force oil further back in shafts.

b. Increased oil feed holes to final planetary.

c. More grooves in sun gear pins.

d. Loosened chain by modifying motor mounting center.

<u>2-15-83 - 9th run</u>

Vapor again in third gear.

a. Began removing teeth from clutch packs and increasing drain holes to prevent churning.

b. Several changes to improve oil draining from 1st gear clutch.

<u>2-18-83 - 10th run</u>

Still vapor in high under load.

a. Modified axle shaft to provide additional oil path to rear gear set.

<u>2-22-83 - 11th run</u>

21 min. in high before vapor. Previous 12 min.

a. Increased size of oil holes in axle shaft.

<u>2-22-83 - 12th run</u>

No improvement.

a. Installed oil blocker in between shafts in high clutch assembly. Thrust washer here is unloaded in high and permits large oil bypass. Required modifying shafts.

<u>2-24-83 - 13th run</u>

One hour test in high shows only slight vapor. Will run efficiency test.

<u>2-25-83 - 14th run</u>

Ran tests in first and second. No problem. While running high speed and load tests in third gear, heavy vapor developed. After running at low speed to cool, metallic clicking heard and test stopped.

Overheated final planetary again possibly due to damage done previously.

a. Rebuilding gear set with new gears and pins.

Approximately 90% of test points completed.

<u>3-3-83 - 15th run</u>

Ran tests again in first and second gear with no problems. Transaxle began to heat at high input RPM in high gear only. Puff of smoke when slowing down indicates a hot spot not getting oil at high RPM's.

a. Modified final reduction gearset to force lubricating oil into needle bearings at high speed.

<u>3-7-83 - 16th run</u>

Final reduction gearset still overheating.

a. Started with new final reduction carrier and checked alignment of gear pins.
b. Since alignment was poor, carrier was remachined and rebuilt.
c. Checked out main housing for bore concentricity, O.K.

<u>3-17-83 - 17th run</u>

Still heats up in high gear at high speed.

a. Changed slotted gears for standard ones in carrier.

b. Installed brass thrust washers to funnel oil into carrier gears.
c. Installed plexiglass spacer to observed oil flow back to oil pan while transaxle is running.

3-21-83 - 18th run

Plexiglass cover revealed following:

First gear - plenty of oil at rear for final planetary at speeds to 3000 rpm.

Second gear - small stream of oil at rear at high speeds. Large flow at low speed.

Third gear - up to 2000 rpm oil at rear is sufficient but decreasing. 3000 rpm only slight oil flow at rear planetary set. 4000 rpm no oil at final planetary.

Teardown modifications

a. Blocked one oil feed hole in second gear clutch drum.
b. Blocked one oil hole in third gear inner shaft.
c. Installed new teflon seal on input shaft.
d. Installed new oil blocker ring in high gear clutch assembly.
e. Plugged half of holes in third gear clutch inner hub.
f. Reduced oil holes in chain sprocket shaft.

These changes will force additional oil to rear planetary.

3-22-83 - 19th run

No heating at any speed or load in each gear.

3-23-83 - 20th Run

After efficiency tests, again torn down and inspected. No problem areas are evident.

Unit was handed over for mating to motor in preparation of vehicle installation.

4-7-83

Testing in vehicle on dynamometer shows first gear clutch release is excessively slow. New springs were installed to improve clutch release. Transaxle and motor reinstalled in vehicle.

This development testing took place over a period of nearly four months. Actual number of teardowns exceeds the 20 times itemized here. This effort far exceeded any planned work. For comparison, the ac two-speed transaxle required only three teardowns prior to vehicle installation.

The solution to the lubrication problem came only as a result of installation of a clear plexiglass spacer between the transaxle and the oil pan. As the transaxle was operated at increasing input speeds, the oil to the rear of the system was decreasing. The final planetary gearset ran completely dry at approximately 4000 rpm on the input shaft in high gear.

By reducing the oil flow to the chain, which was regulated by a nylon oil dam at the front end of the transaxle, more oil was forced to the rear and the final planetary. This seemingly trivial alteration proved to be the solution to a most perplexing problem.

As a final test, the transaxle was operated at full load in third gear, 48 lb-ft and 4000 rpm for one hour. At the end of that time, the temperature of the oil had stabilized at 170°F, a safe temperature. The unit was torn down again to inspect the gears and bearings, which were in excellent condition.

6.2.4 Efficiency Testing and Results

Efficiency testing consisted of operating the transaxle over the entire input speed range the motor could provide at torque loads from six lb-ft (except as noted) to 96 lb-ft. Some extremes could not be tested as they would exceed the transaxle output shaft torque limit (as in the two-speed testing the differential was locked and all power was taken from a single output shaft).

The results following in Table 4 include power to operate the small hydraulic pump operating the clutches and providing lubrication, 150 watts. Also, a correction had to be made for losses on the input from the dynamometer bearings and universal joints between the input torque transducer and the transaxle. By spinning the input shaft with the input chain to the transaxle uncoupled, the drag was measured as a function of input speed. Below 1000 rpm the drag was 0.6 lb-ft, and at 1500 rpm and above it was 0.7 lb-ft. Compensation of a more precise nature is beyond the accuracy of the test equipment.

No compensation was made for a small error due to loading of the transaxle output shaft from the dynamometer bearings and universal joints between the output torque transducer and the transaxle. Because of the relatively high torque levels, the error is considered negligible but would tend to raise the overall efficiency at light loads if it had been compensated for.

TABLE 4

MEASURED TRANSAXLE EFFICIENCY

RPM	4	6	12	24	36	48	Input Torque - lb-ft
300	45.5	55.9	69	76.7	81.1	84.1	
500	52.9	59.8	74.9	82.8	86	87.1	EXCEEDS SINGLE OUTPUT
1000	54.8	66.6	79.6	85.9	87.7	88.2	SHAFT TORQUE RATING
1500	58.9	70.1	81.8	87.2	88.6	88.9	
	*4.5						
2000	66.5	74.8	83.7	87.9	89.3	89.4	1st GEAR
	*2.7						
2500	47.4	73.2	83.8	88.3	89.4	89.5	
	*2.8						
3000	43.1	72.7	82.9	88.2	89.3	89.6	
	*3.2						
3500	48.6	71.8	83.2	87.7	88.9	89.4	
	*3.1	*6.9					
4000	39.2	73	82.1	87.5	88.8	89.1	

RPM	4	6	12	24	36	48	60	72	84	lb-ft
300	45.3	54.7	68.2	77.5	81.1	83				
500	55.7	64.2	76.1	82.7	84.5	85.7	86.2	86.3	86.2	
1000	64.1	71.6	81.0	86.1	87.3	87.8	87.9	87.7	87.8	EXCEEDS
	*4.6									SINGLE OUTPUT
1500	71.7	75.3	83.2	87.4	88.1	88.4	88.4	88.5	88.7	SHAFT TORQUE
	*2.1									RATING
2000	55.0	78.8	84.0	88.4	89.2	89.2	89.5	89.1	88.9	
	*2.5									
2500	52.3	78.6	84.1	87.7	89.5	89.3	89.5	89.3	89.3	2nd GEAR
	*2.8	*6.9								
3000	53.2	77.6	85.2	88.5	89.6	89.4	89.8	89.9		
	*3.1	*7.3								
3500	57.4	78.1	84.3	88.1	89.4	89.9	89.9			
	*3.4	*7.4								
4000	52.0	76.7	84.5	88.2	89.4	90.0				

RPM	4	6	12	24	36	48	60	72	84	96	lb-ft
300	32.0	53.5	70.2	80.7	86.1	88.4					
500	28.5		75.4	84.1	87.6	90.0	91.1	91.7	92.4	92.8	
1000	41.8		8.15	87.7	90.6	91.9	92.6	93.2	93.5	93.8	
1500	52.2		87.7	88.6	91.0	92.8	93.5	94.1	94.4	94.6	3rd
2000	62.8		88.9	90.3	92.6	93.6	94.5	94.3	95.0	95.2	GEAR
2500	63.7		89.7	93.4	92.9	94.8	94.6	94.5	95.1		
3000	62.7		90.2	93.6	93.8	95.4	95.5	94.6			
3500	70.0		89.3	93.8	94.7	96.0	95.6				
4000	71.4		87.5	92.9	94.8	95.6					

Notes: *Actual input torque at these test points
1. corrected for 150w hydraulic pump power
2. corrected for test fixture U joint loss
3. rated motor torque is 60 lb-ft, continuous

The following graphs, Figures 6.2.4-1 through 6.2.4-3 show transaxle efficiency as a function of per-unit load with respect to input rpm. In low gear the transaxle operates over the complete range, 0-4000 rpm. In second and third gears the input is at motor base speed and above, and the graphs show the operating area as above 2000 rpm.

Figures 6.2.4-4 through 6.2.4-8 show efficiency as a function of speed in each gear with respect to input torque. The graphs show efficiency of all three gears at each speed even though second and third gears do not operate below 2000 rpm input speed.

The results show that the efficiency is high at nearly all operating conditions, and excellent results were expected in the vehicle.

6.2.5 Predicted Efficiency in the Vehicle

Based on the transaxle tests, an estimate of efficiency versus road speed in the vehicle was made, both for steady speed loads and maximum acceleration loads. The following graph, Figure 6.2.5-1, shows the expected efficiencies. Even with the high efficiencies measured on the dynamometer, the road loads below 20 mph are so small that only when accelerating is the low gear efficiency very high.

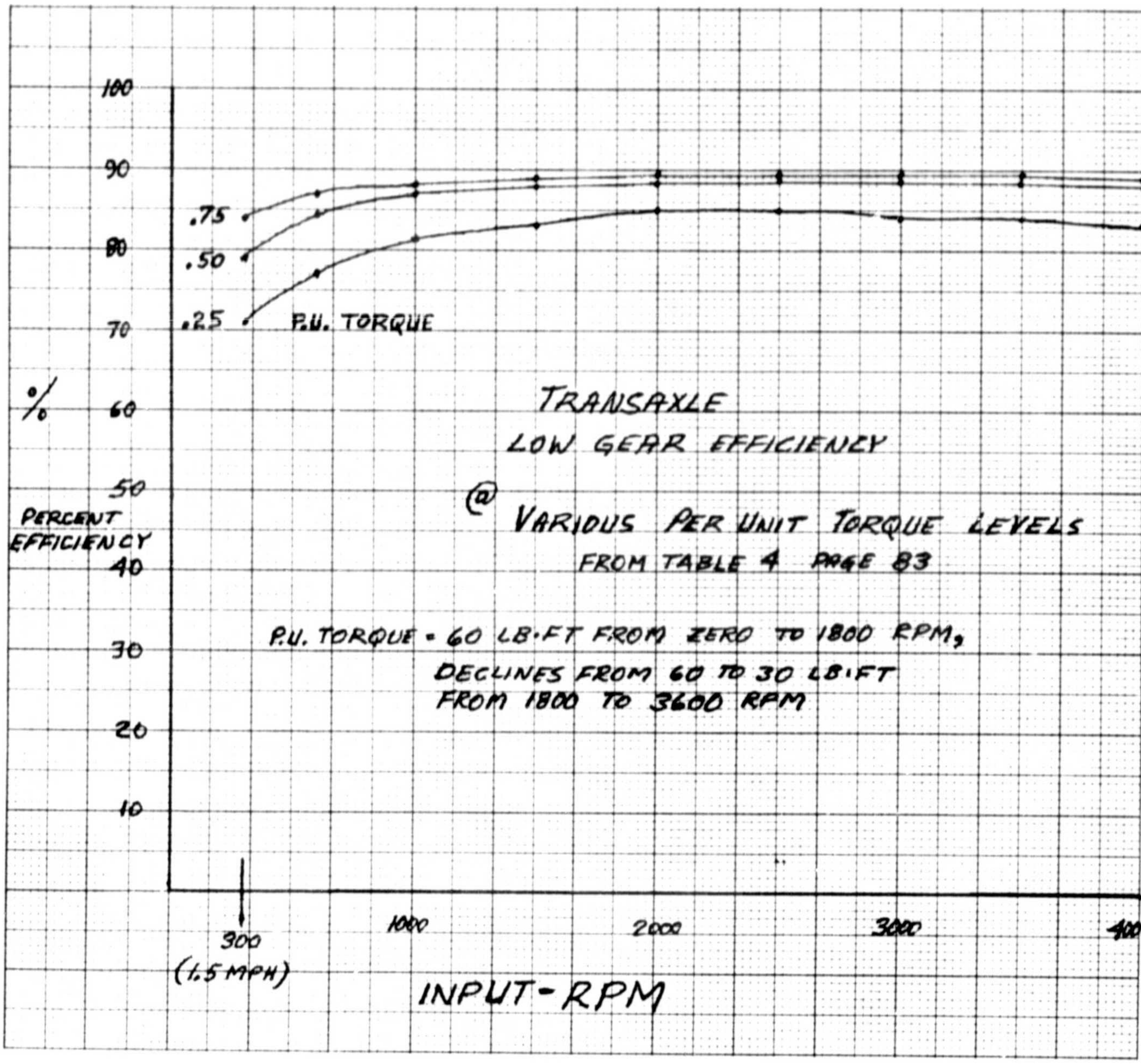

100
90
80
70
60
50
40
30
20
10
% PERCENT EFFICIENCY
.75
.50
.25
P.U. TORQUE
TRANSAXLE
LOW GEAR EFFICIENCY
@ VARIOUS PER UNIT TORQUE LEVELS
FROM TABLE 4 PAGE 83
P.U. TORQUE = 60 LB·FT FROM ZERO TO 1800 RPM,
DECLINES FROM 60 TO 30 LB·FT
FROM 1800 TO 3600 RPM
300
(1.5 MPH)
1000
2000
3000
4000
INPUT-RPM

Figure 6.2.4-1

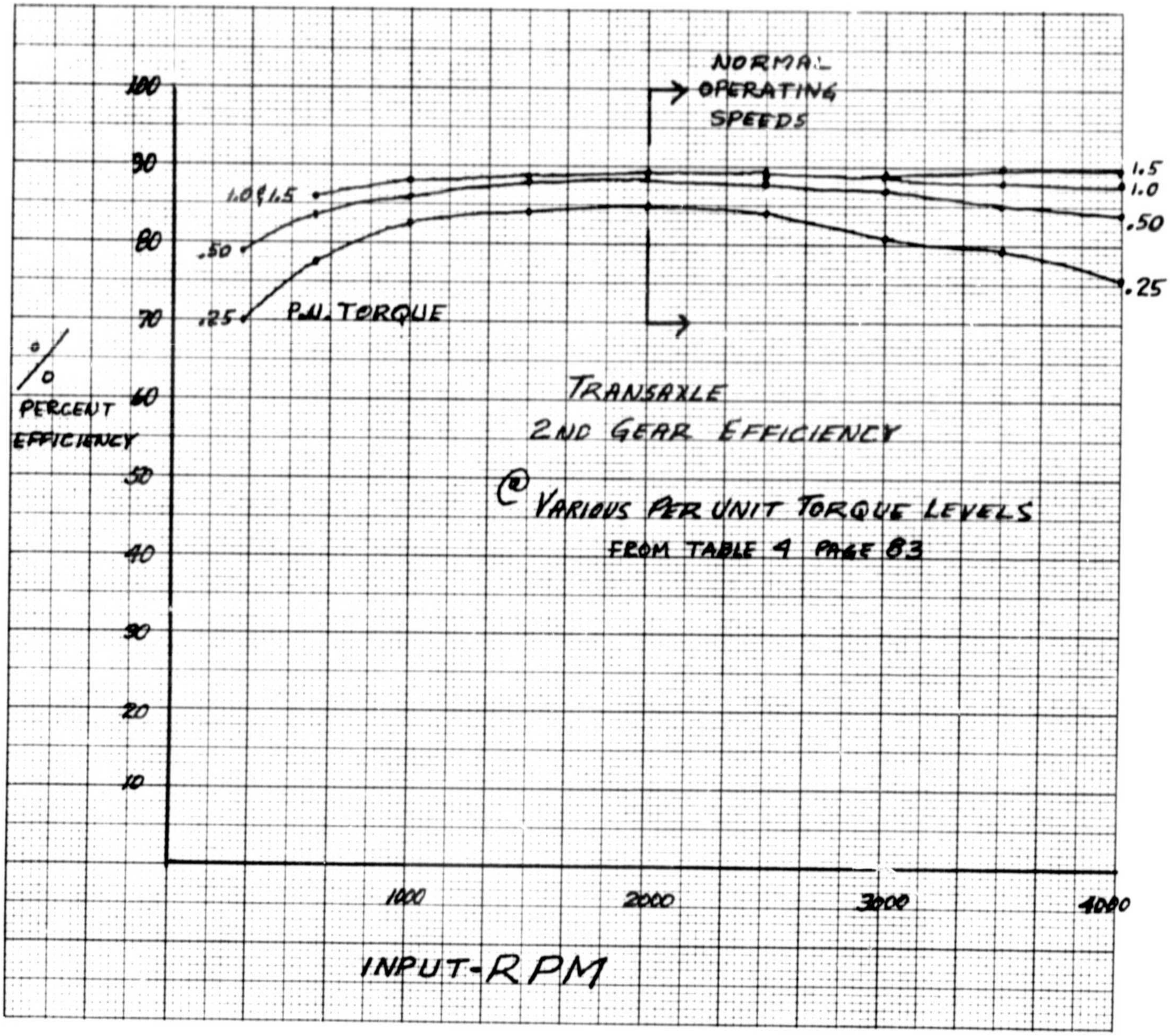

NORMAL OPERATING SPEEDS
100
90
80
70
60
50
40
30
20
10
% PERCENT EFFICIENCY
1.0 & 1.5
.50
.25
P.U. TORQUE
1.5
1.0
.50
.25
TRANSAXLE
2ND GEAR EFFICIENCY
@ VARIOUS PER UNIT TORQUE LEVELS
FROM TABLE 4 PAGE 83
1000
2000
3000
4000
INPUT-RPM

Figure 6.2.4-2

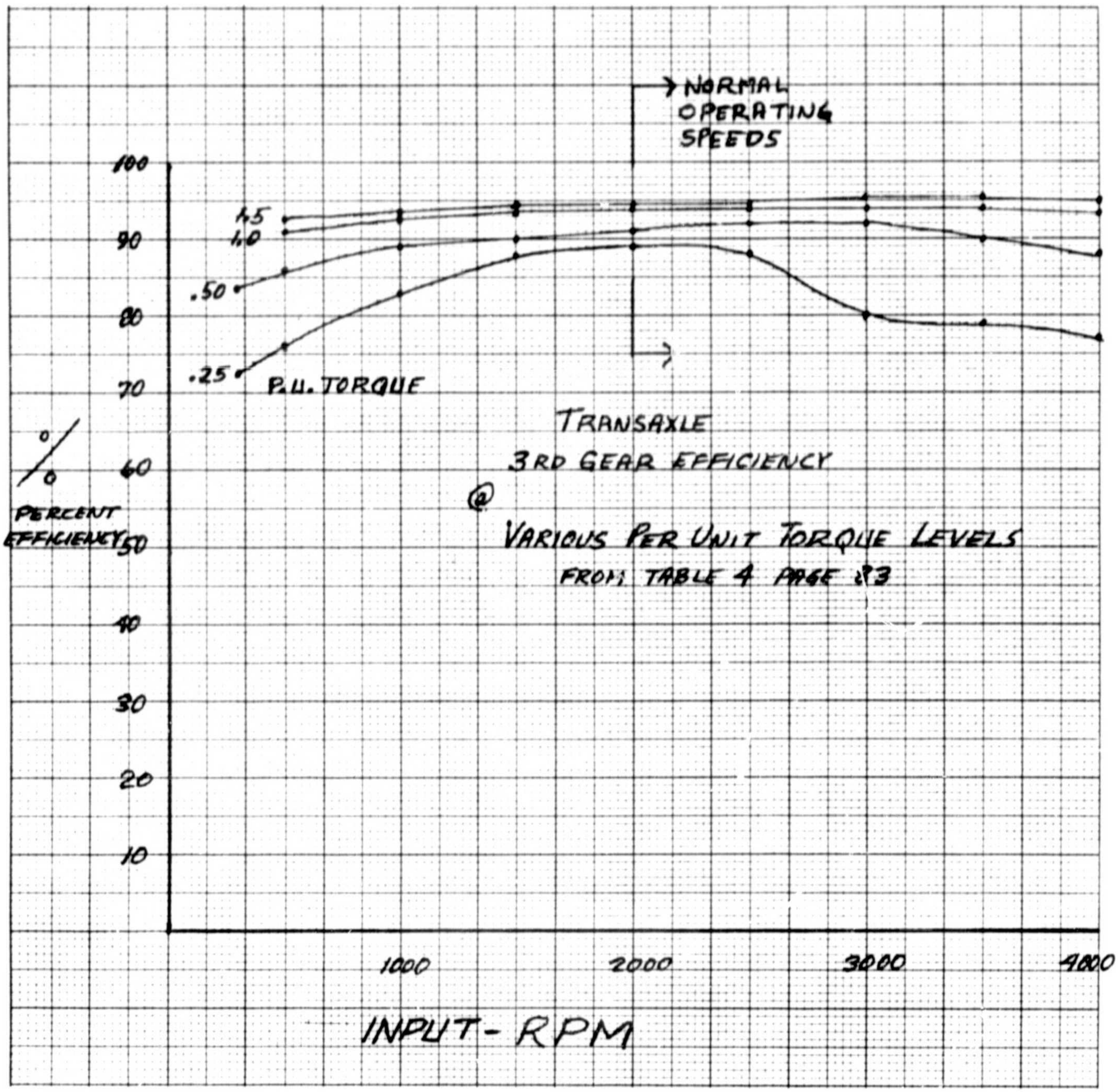

NORMAL
OPERATING
SPEEDS
100
90
80
70
60
50
40
30
20
10
1.5
1.0
.50
.25
P.U. TORQUE
%
PERCENT
EFFICIENCY
TRANSAXLE
3RD GEAR EFFICIENCY
@
VARIOUS PER UNIT TORQUE LEVELS
FROM TABLE 4 PAGE 83
1000
2000
3000
4000
INPUT - RPM

Figure 6.2.4-3

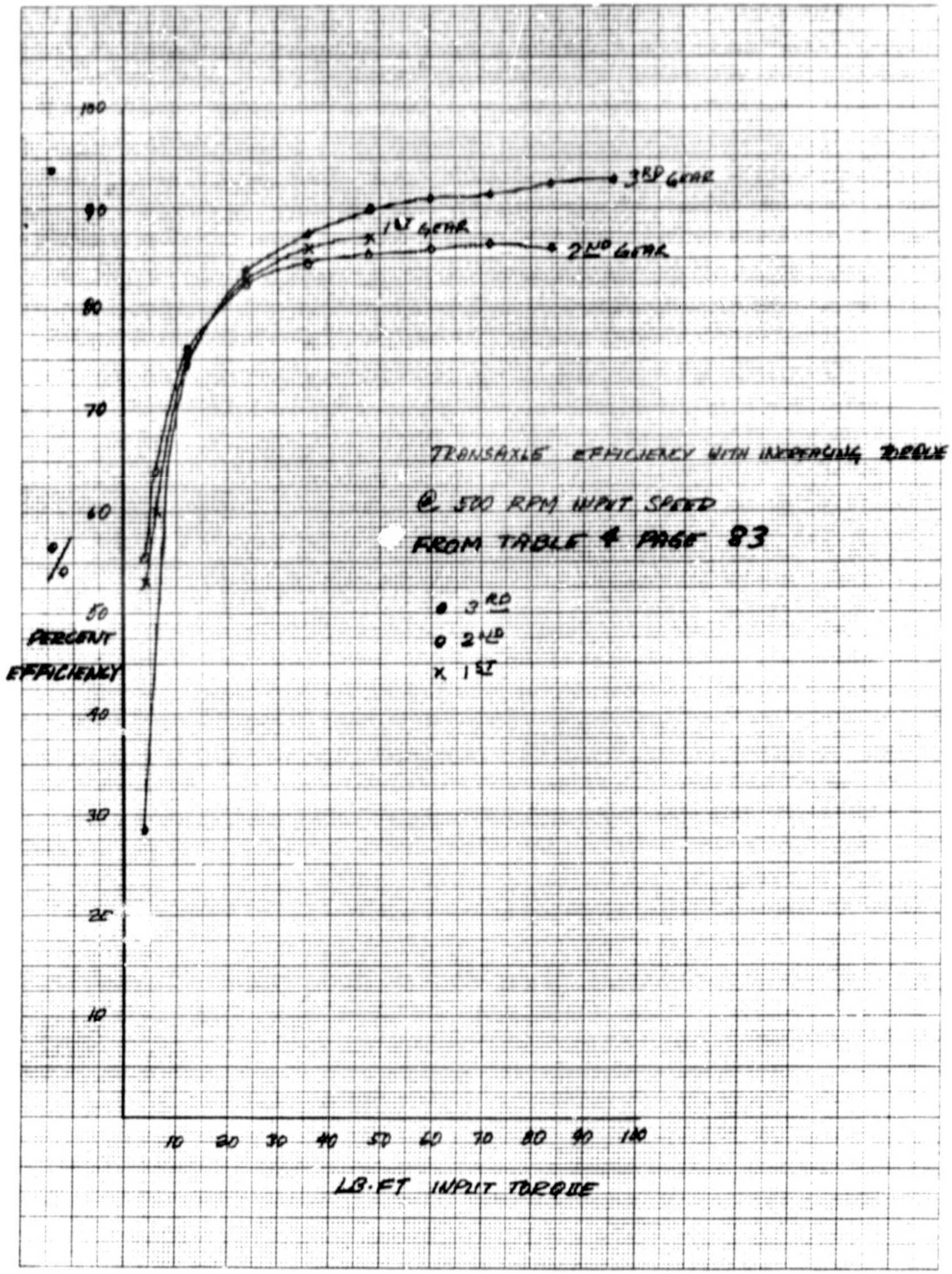

TRANSAXLE EFFICIENCY WITH INCREASING TORQUE
@ 500 RPM INPUT SPEED
FROM TABLE 4 PAGE 83
3RD GEAR
1ST GEAR
2ND GEAR
• 3RD
o 2ND
x 1ST
PERCENT EFFICIENCY
%
LB·FT INPUT TORQUE

Figure 6.2.4-4

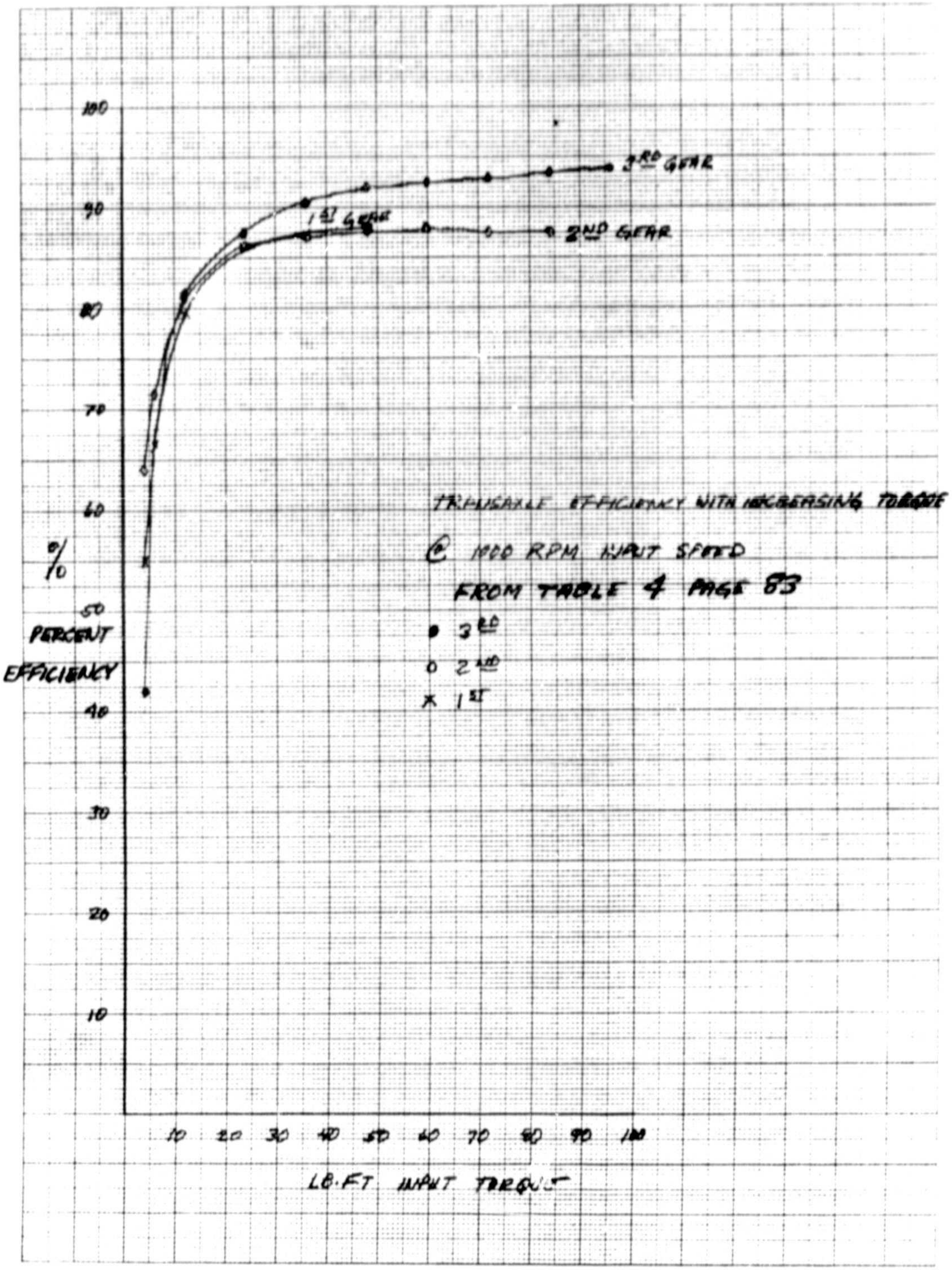

3RD GEAR
1ST GEAR
2ND GEAR
@ 1000 RPM INPUT SPEED
FROM TABLE 4 PAGE 83
3RD
2ND
1ST
%
PERCENT
EFFICIENCY
100
90
80
70
60
50
40
30
20
10
10 20 30 40 50 60 70 80 90 100
LB·FT INPUT

Figure 6.2.4-5

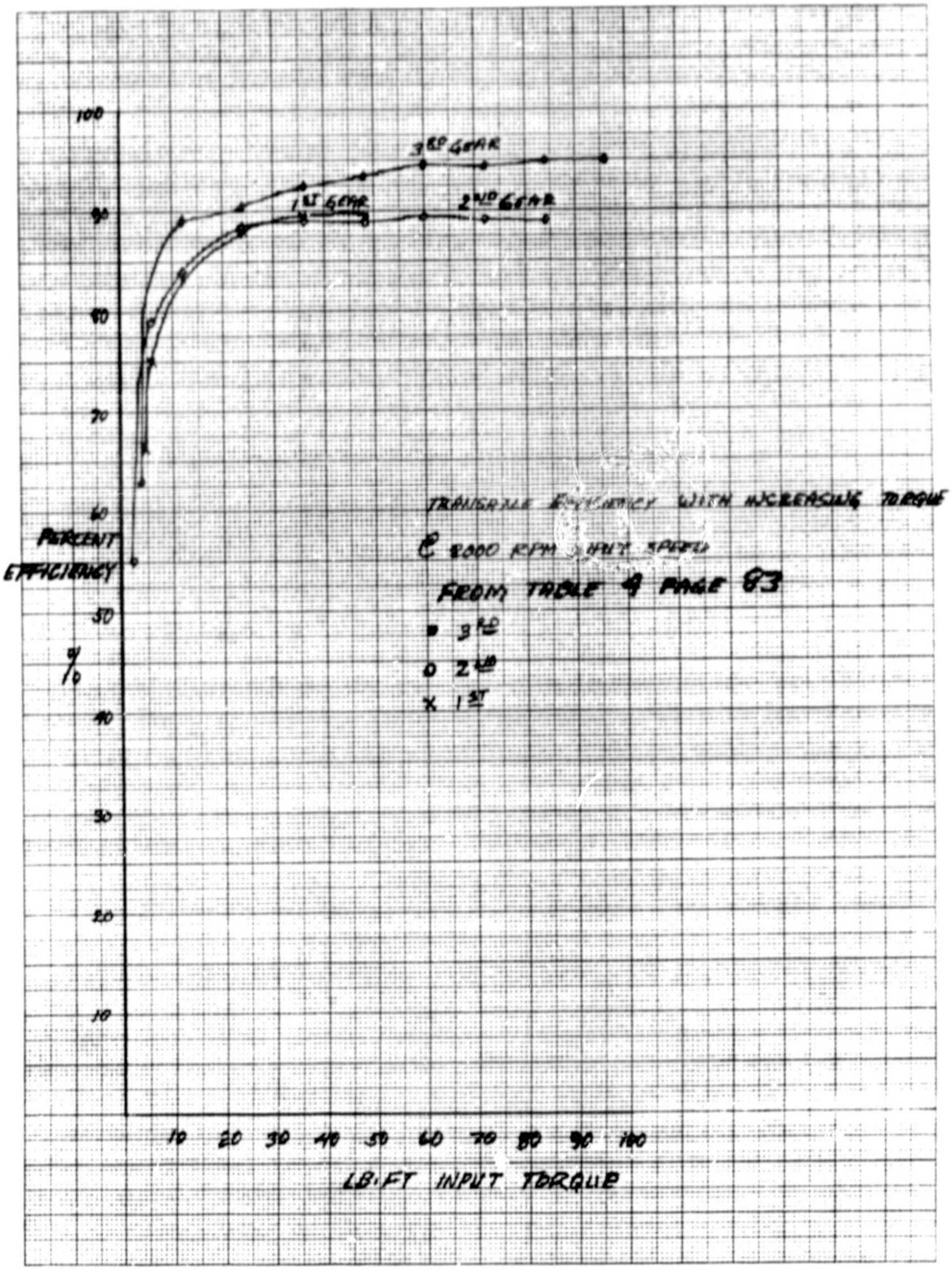

3RD GEAR
1ST GEAR
2ND GEAR
100
90
80
70
60
PERCENT EFFICIENCY
50
%
40
30
20
10
10 20 30 40 50 60 70 80 90 100
LB·FT INPUT TORQUE
FROM TABLE 4 PAGE 83
• 3RD
o 2ND
x 1ST

Figure 6.2.4-6

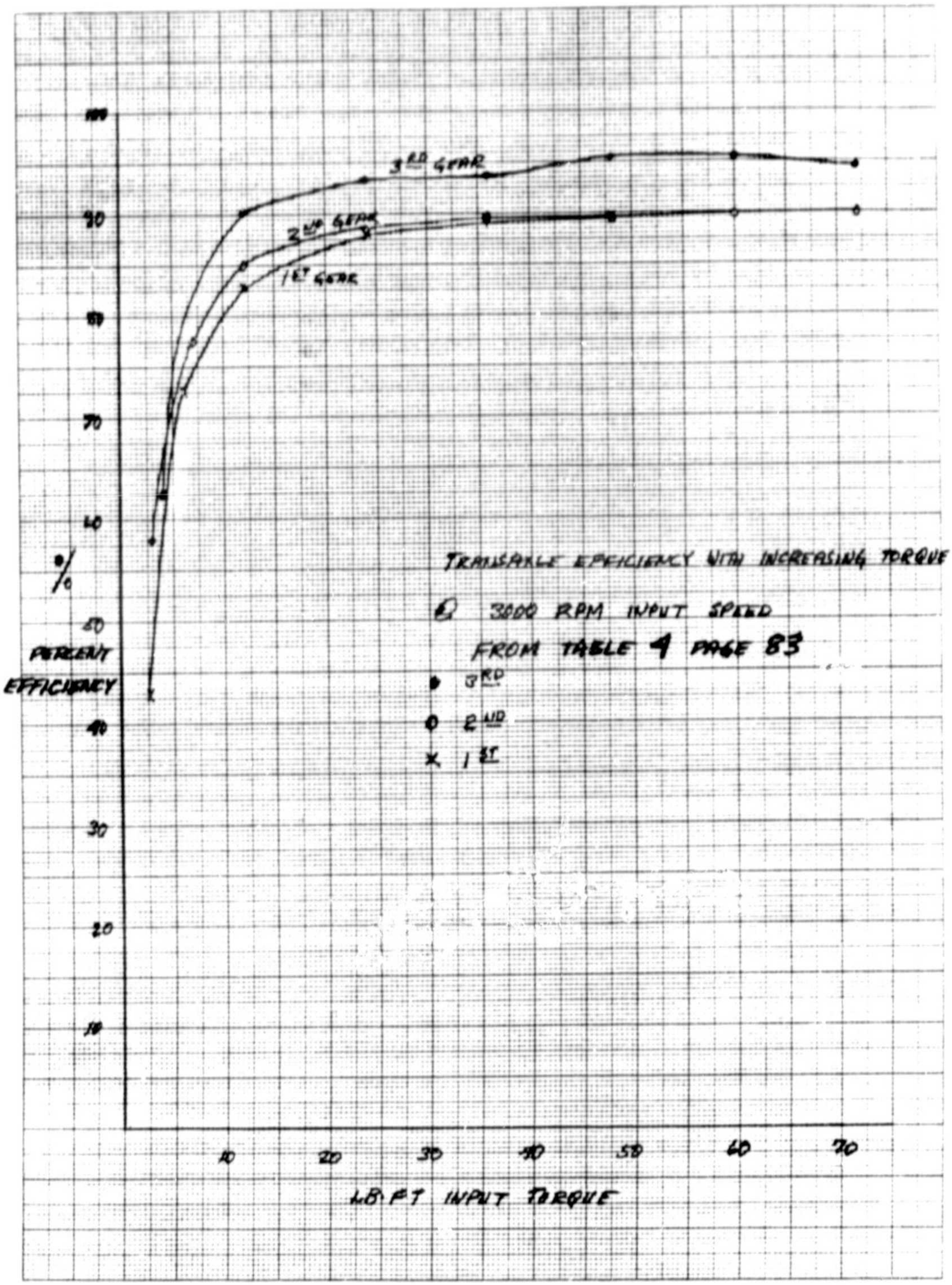

3RD GEAR
2ND GEAR
1ST GEAR
TRANSAXLE EFFICIENCY WITH INCREASING TORQUE
@ 3000 RPM INPUT SPEED
FROM TABLE 4 PAGE 83
3RD
2ND
1ST
%
PERCENT EFFICIENCY
LB FT INPUT TORQUE

Figure 6.2.4-7

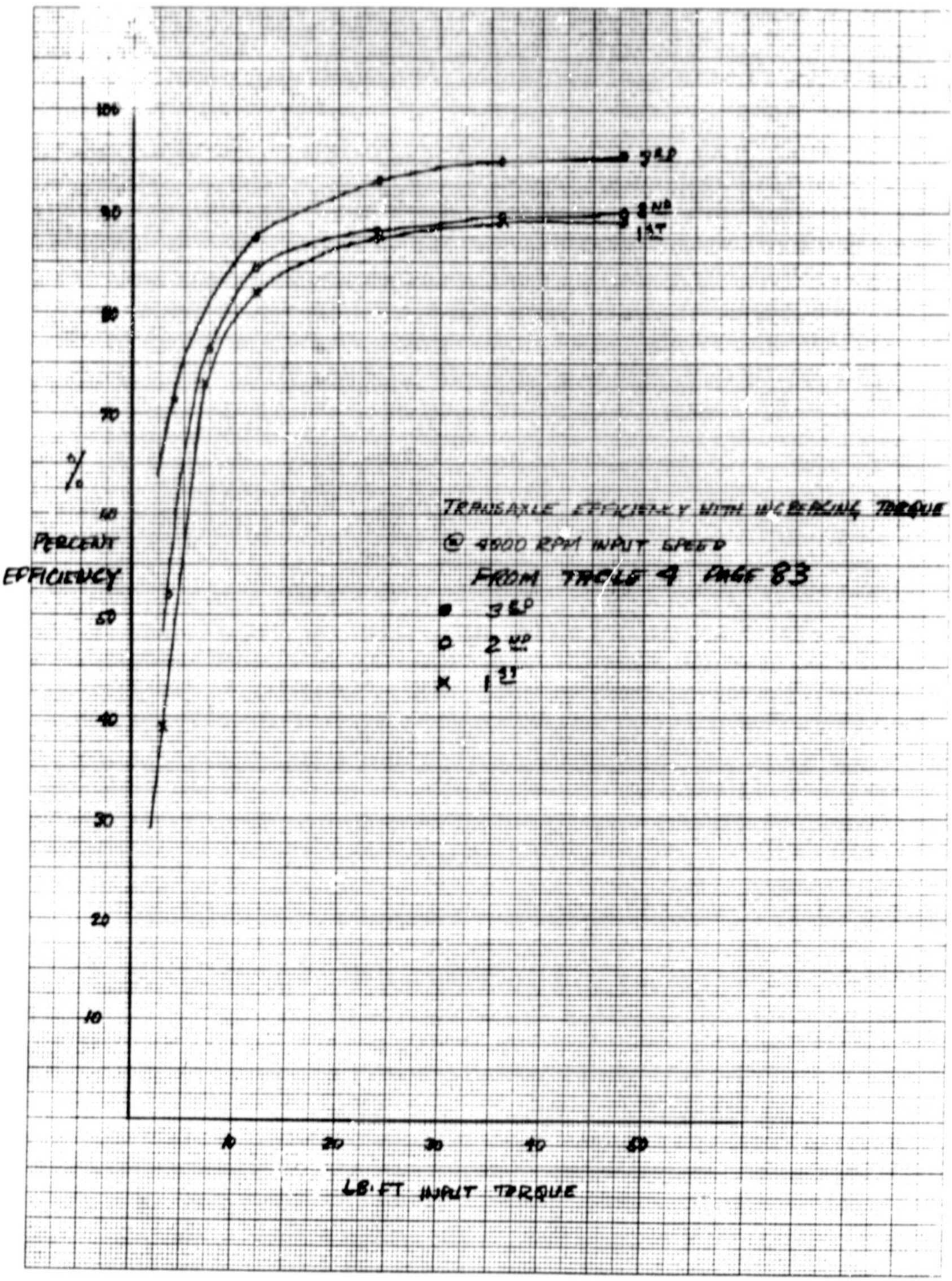

TRANSAXLE EFFICIENCY WITH INCREASING TORQUE
@ 4800 RPM INPUT SPEED
FROM TABLE 4 PAGE 83
3RD
2ND
1ST
% PERCENT EFFICIENCY
LB·FT INPUT TORQUE

Figure 6.2.4-8

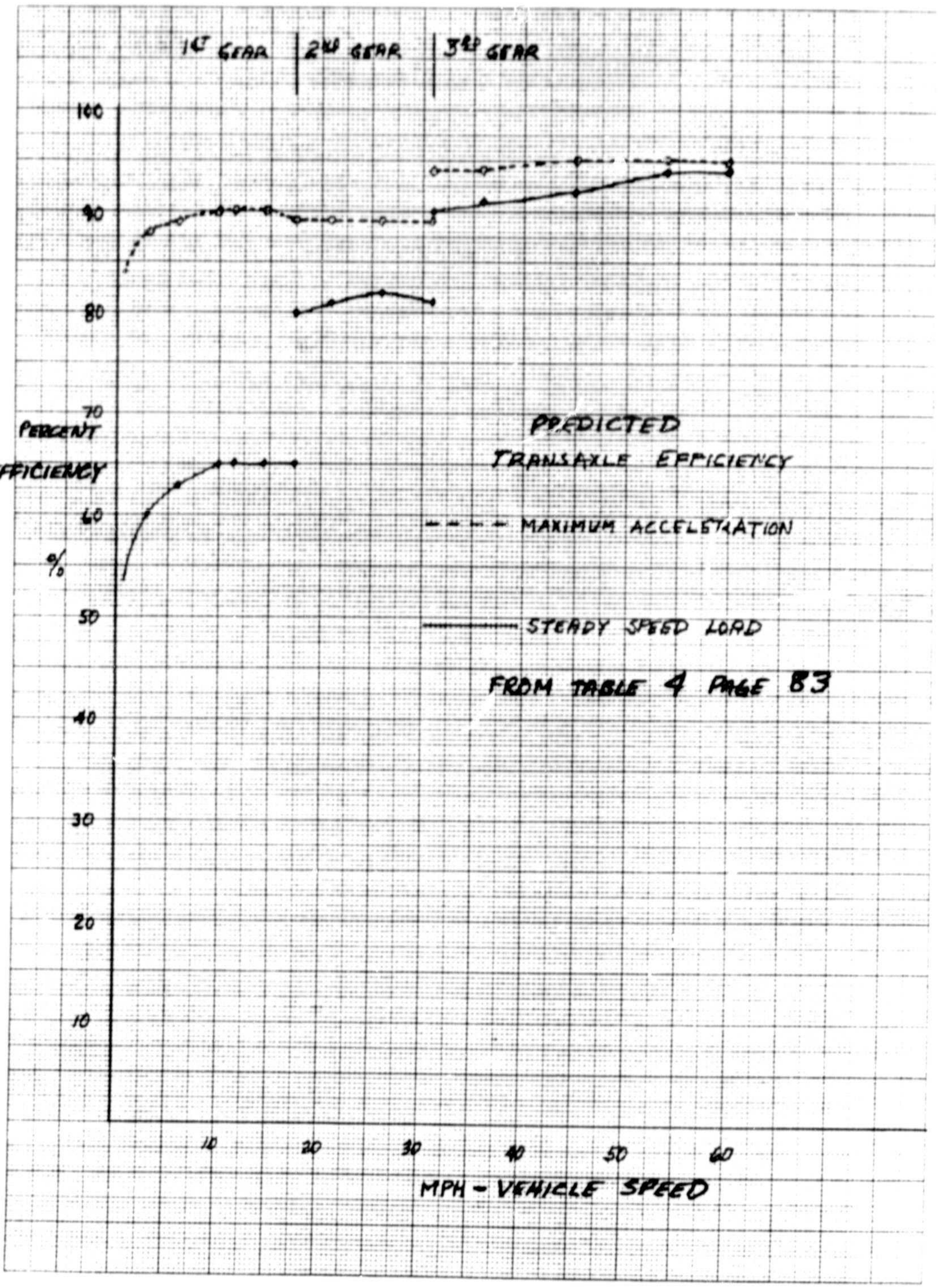

1ST GEAR
2ND GEAR
3RD GEAR
PERCENT EFFICIENCY %
PREDICTED TRANSAXLE EFFICIENCY
MAXIMUM ACCELERATION
STEADY SPEED LOAD
FROM TABLE 4 PAGE 83
MPH - VEHICLE SPEED

Figure 6.2.5-1

6.3 Combined Motor-Controller-Transaxle Performance Predictions in the Vehicle

Based on the individual component tests and the calculated vehicle road loads, it is possible to make estimates of system performance and efficiency.

6.3.1 Efficiency - Cruising and Accelerating

Figure 6.3.1-1 shows combined motor-controller-transaxle efficiency as a function of steady speed road loads. Again, efficiency at low speeds reflects the small power required to move the vehicle at these speeds. Figure 6.3.1-1A shows the effect on efficiency from raising the shift point speeds. The final tuning of the system has the shift points at 23 and 41 mph. Figure 6.3.1-2 shows the efficiency during hard acceleration. Here the efficiency is never as low as in the previous graph, but because motor efficiency is lower at high load, the maximum efficiency is seldom above 70%.

Actual operation of the vehicle will be a combination of these two sets of data, acceleration efficiency and cruising efficiency.

6.3.2 Energy Use Per Mile

With the system efficiency at steady speed loads and the calculated vehicle road loads, a predicted input power and energy consumption graph was generated. Figure 6.3.2-1 shows road load as a function of vehicle speed in hp. Next is the curve indicating actual bus input power based on system efficiency. From the bus power and vehicle speed, the watt-hour per mile energy consumption curve is generated. Based on these predictions, the vehicle energy consumption should be quite good between 15 mph and 50 mph.

COMBINED MOTOR-CONTROLLER - TRANSAXLE PERFORMANCE IN THE VEHICLE

PREDICTIONS

Steady Road Speed Efficiency

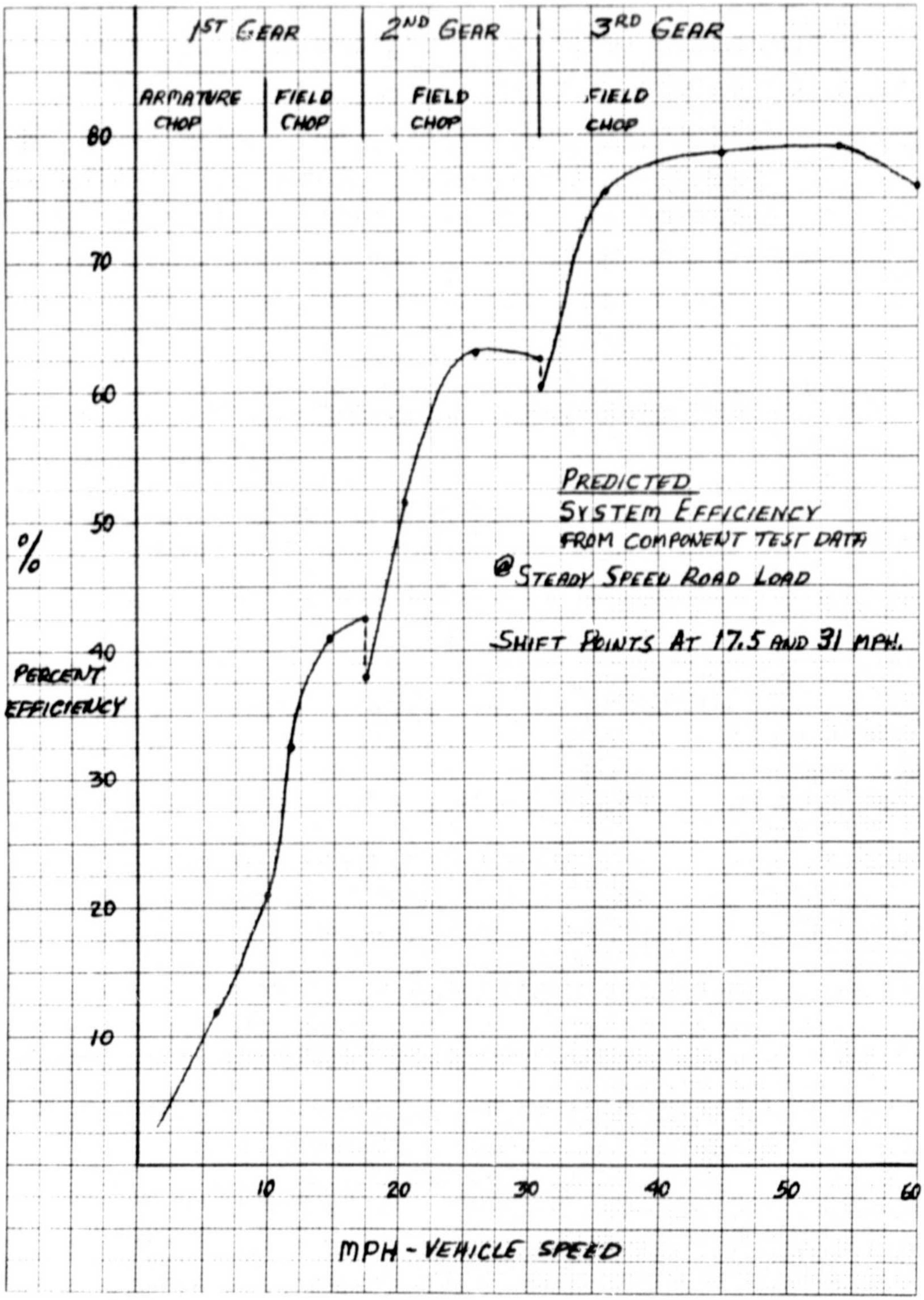


Figure 6.3.1-1

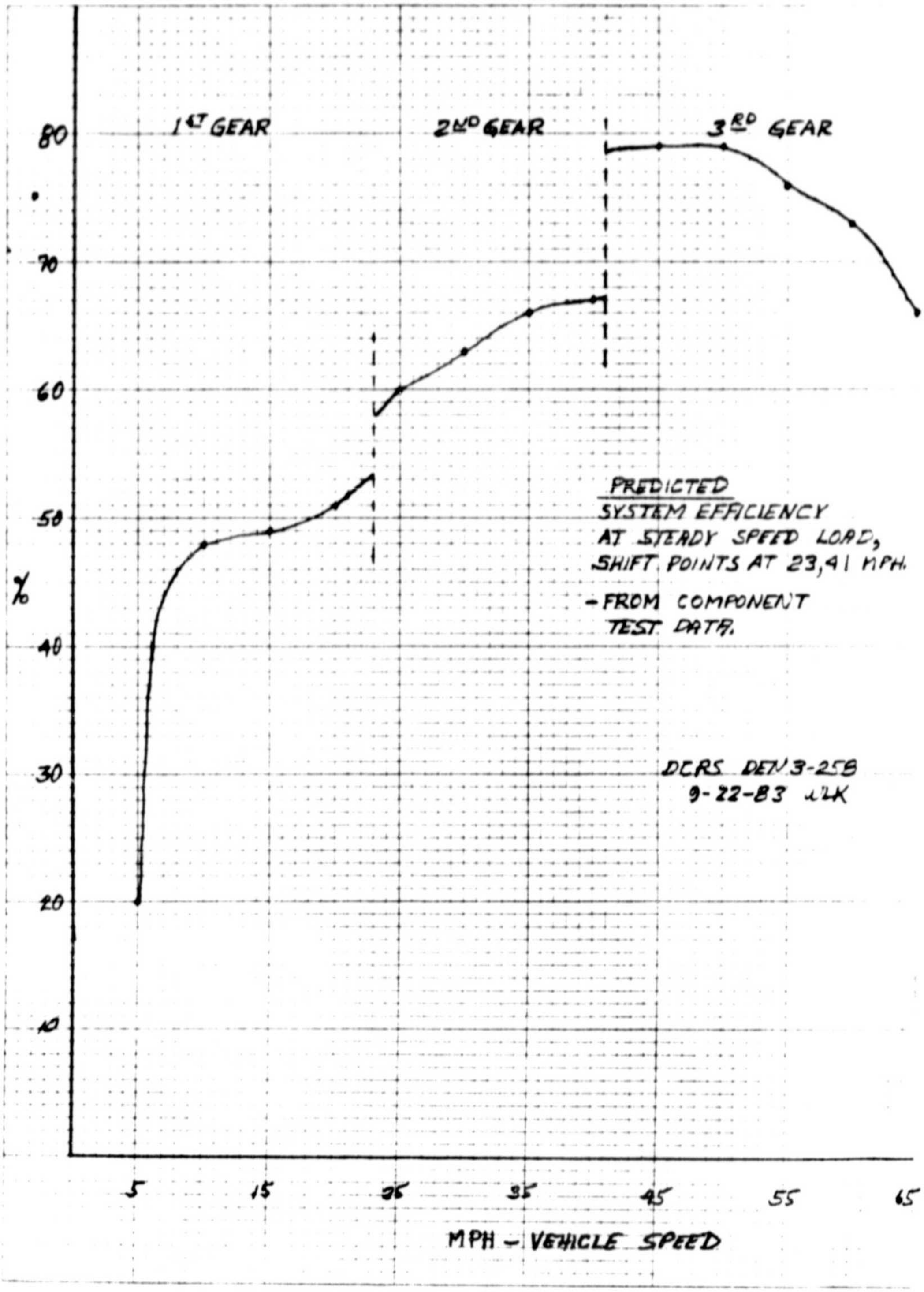


Figure 6.3.1-1A

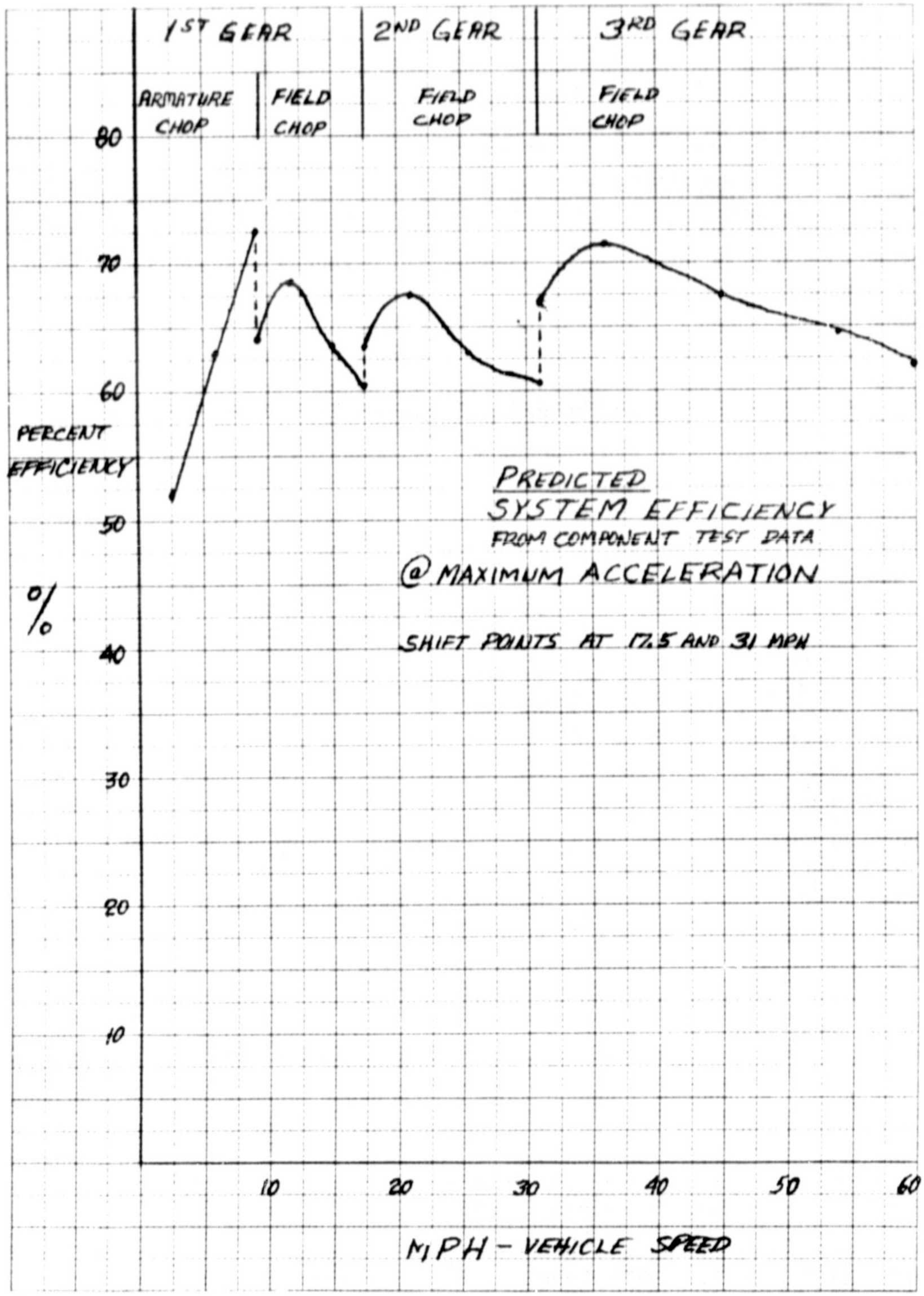

1ST GEAR
2ND GEAR
3RD GEAR
ARMATURE CHOP
FIELD CHOP
FIELD CHOP
FIELD CHOP
80
70
60
50
40
30
20
10
PERCENT EFFICIENCY
%
PREDICTED
SYSTEM EFFICIENCY
FROM COMPONENT TEST DATA
@ MAXIMUM ACCELERATION
SHIFT POINTS AT 17.5 AND 31 MPH
10
20
30
40
50
60
MPH - VEHICLE SPEED

Figure 6.3.1-2

Maximum Acceleration Efficiency

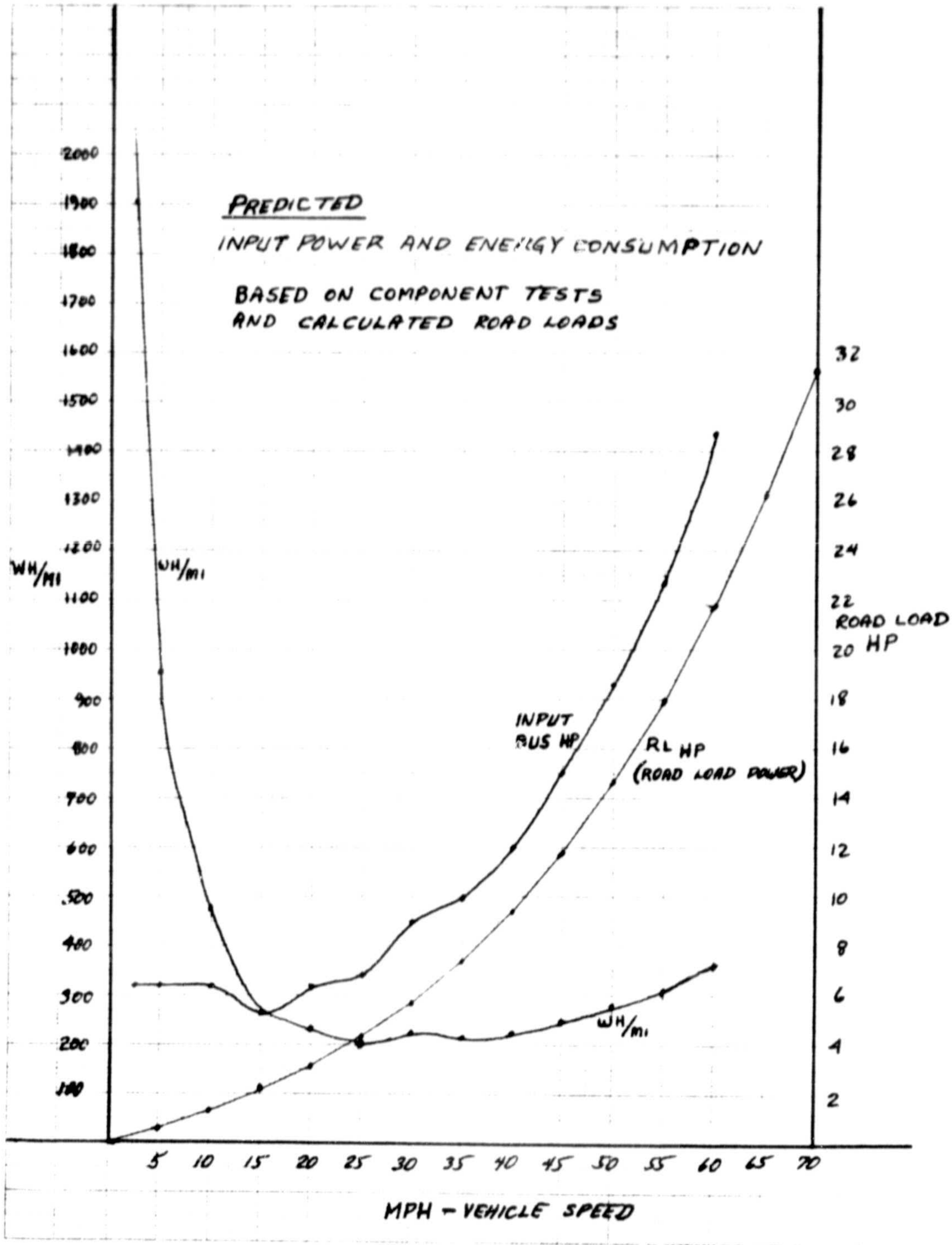


Figure 6.3.2-1

7.0 INSTALLATION

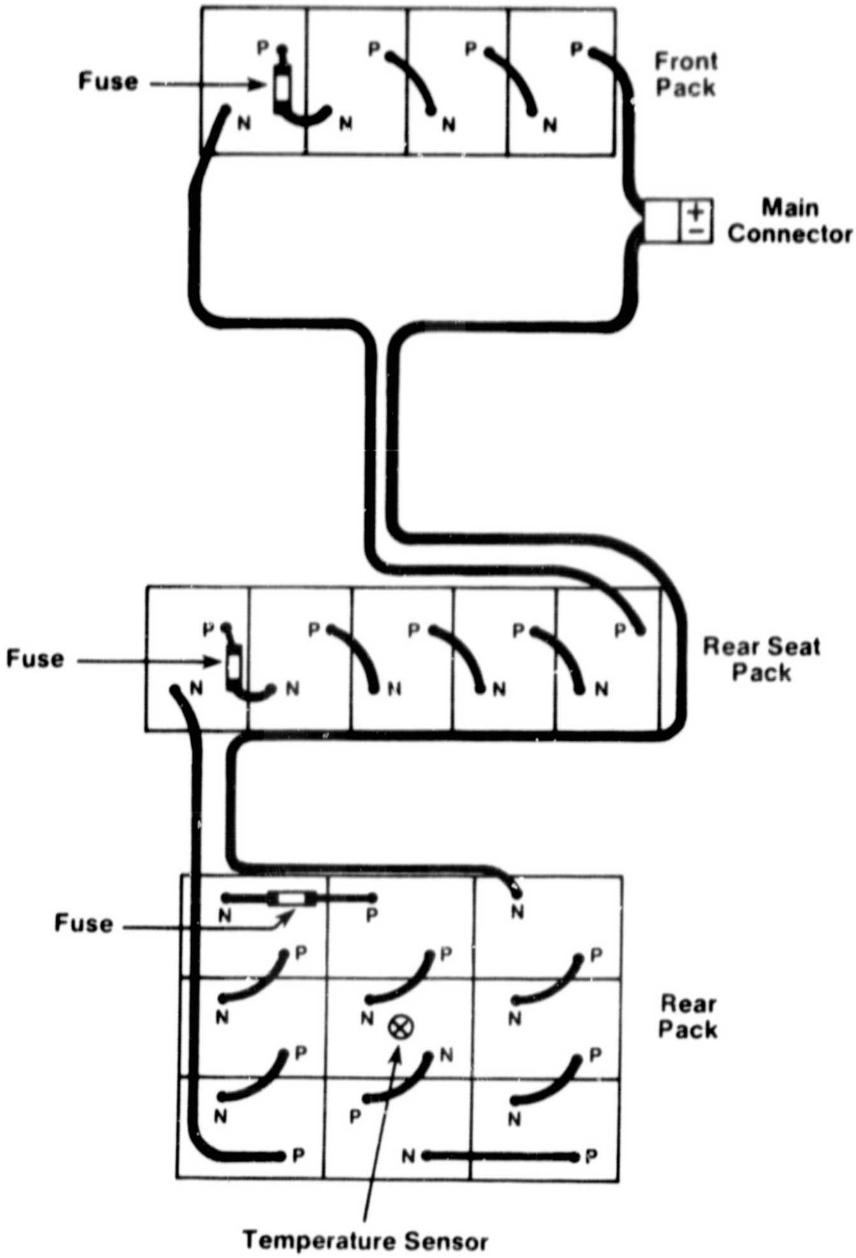
7.1 Vehicle Preparation

This vehicle was intended for installation of an AC propulsion system and became available for the DC program when the AC program was modified. Specific vehicle characteristics of design are included in the final report of the AC Phase 2 program.

7.1.1 Battery Installation

Differences from the AC vehicle are relatively minor. The batteries were rearranged to allow installation of the controller under the hood. Batteries are mounted in fabricated steel angle racks rather than the fiberglass carriers designed for the AC system. This is because the DC system operates at the near term voltage of 108 vdc and uses the 6v batteries which are a different size than the 12v units used for ac. There are nine batteries in the rear trunk area, five batteries under the rear seat and four under the hood, just inside the grille. The batteries under the rear seat and those in the trunk are connected by a tube that permits air to be drawn through both and discharged behind the rear bumper. There are two exhaust fans, a 110 vac fan when the batteries are charging and a 12 vdc fan when the vehicle is being driven. The batteries under the hood have a ventilated fiberglass cover but no forced ventilation. See battery location, Figure 7.1.1-1.

The batteries are all connected in series with 2/0 gauge wire which is adequate for 250 amps of continuous current.



Traction Battery Location and Wiring

Figure 7.1.1-1

7.1.2 Suspension Modifications

With added battery weight in the rear the coil springs were replaced with higher rate springs to support approximately an additional 300 lbs. Shock absorbers and front springs were not modified. Front wheel loading is virtually identical to that of the ac system.

7.1.3 Instrument Panel Modifications

All vehicle accessories, windshield wipers, radio, lights, heater, etc., are functional. In place of a fuel gauge is a Curtis, battery state-of-charge meter. The old fuel gauge indicates kerosine for the passenger compartment heater. The engine temperature gauge now indicates motor case temperature. See instrument panel, Figure 7.1.3-1.

Below the battery state-of-charge meter are four indicator lights. The "fail" light indicates a logic or chopper failure causing the controller to shut the system down. The "limit" light indicates the system is operating at the current limit, or maximum power. This is an inefficient operating condition. The "12v low" light indicates a failure of the on-board DC-to-DC converter that maintains the 12v auxiliary battery. The fourth light, "Charge," indicates the charge cable is connected to the vehicle. The vehicle will not start with the cable connected but this alerts the driver as to why the vehicle will not operate.

In the center of the dashboard on either side of the heater controls are two gauges and four lights to monitor vehicle operation. The left gauge indicates bus current and the right gauge

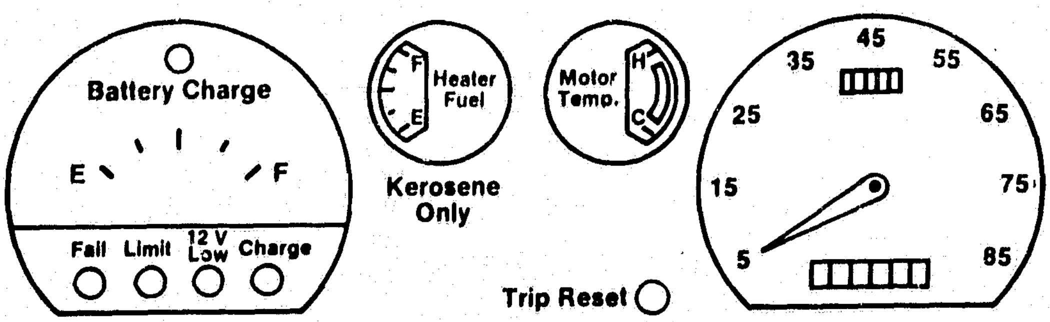


Figure 7.1.3-1 Instrument Panel

bus voltage. Above the left gauge are a green and three yellow indicator lights. The green indicates the vehicle is in neutral; the yellow lights indicate which gear the transmission is operating in. From left to right, first, second and third gear. See Figure 7.1.3-2.

The vehicle has a new gear selector, a modified T handle type. There are four positions only. All the way forward is park, then a wide gap and reverse. Next is neutral, and last is drive. Since the controller must select the proper gear for vehicle and motor speed, a driver option for first or second gear cannot be allowed.

7.1.4 On-Board Charger

The on-board charger was purchased from DC Systems Inc. and repackaged to fit under the hood, no other changes being made. It is a simple, ferroresonant, tapering charge type. The charger will accept 208 or 220 vac input. A switch on top of the charger changes the tap on the transformer to the desired voltage. Output of the charger is limited to approximately 30 amps and tapers to 2-3 amps as the battery voltage rises. A meter on the side of the charger indicates output current to the batteries. A 30 amp circuit breaker is built into the front of the charger for safety. There are two charger outputs, the 108 vdc at up to 30 amps and 12 vdc at up to 12 amps for the auxiliary battery. On-off control and timer for the charger are located inside the charge hatch, formerly fuel fill cover. When the charge cable is connected, rotating the timer switch will turn on the charger and a pilot light at the timer. The time, in hours, for charging, is set and the charger will be turned off automatically.

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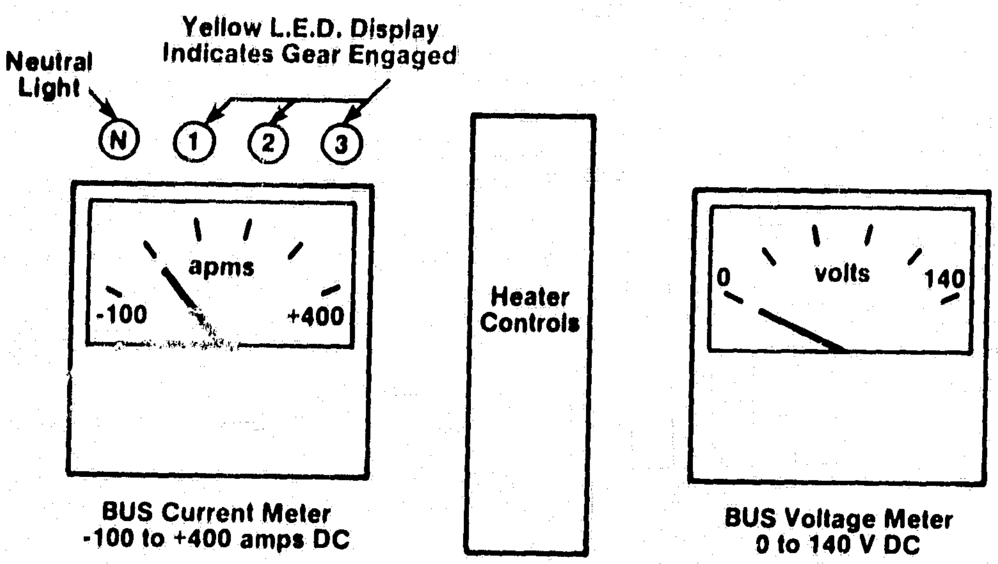

Vehicle Propulsion System Status Display

Figure 7.1.3-2

7.1.5 Vehicle Wiring

All accessory wiring was left intact except that removed with the engine system. Battery cables were added, 2/0 gauge to carry up to 350 amps. Cables run from the rear trunk compartment battery to the batteries under the rear seat and up to the four batteries under the hood.

The charger cable comes from the charge hatch into the rear battery pack and follows the battery cables forward. At the rear of the vehicle, behind the bumper, are two vent fans, one 110 vac and one 12 vdc. All the cables run through the battery compartment and under the center of the vehicle floor to the underhood area.

Behind the center console, up against the firewall, is the vehicle interface box. The start and latch relays that connect the vehicle 12v system to the 108v traction system are here. The "12v low" monitor and motor temperature sensor are located here also. The high and low voltage systems are kept isolated from each other. The vehicle wiring diagram show all added wiring and identifying numbers.

7.2 Motor-Transaxle Assembly

The motor and transaxle are connected together by a mating adaptor, essentially a plate with two holes, to establish the center to center distance between them. The motor and transaxle are face mounted into pilot holes with "O" ring seals. The rear end of both are connected together by the mount that supports them in the vehicle.

Power is transmitted from the motor by means of a HY-VO chain running in the cavity created within the mating adaptor when the chain cover is installed. The chain is lubricated from the transaxle and oil flows back to the sump from the bottom of the chain case.

7.3 Motor-Transaxle Installation

The motor and transaxle assembly is mounted at three points in the vehicle. Each point has a rubber sprung motor mount to give some resilience. Because the DC motor has a larger diameter than the AC, the front mount in the vehicle was modified by drilling new mounting holes approximately one inch further forward. The other two mounting positions are unchanged.

The center to center distance between output flanges is the same as the ac two-speed transaxle. The axle shafts and universal joints are therefore the same as used for the two-speed.

To provide for clean air to cool the motor a baffled plenum was installed in the area normally occupied by the vehicle radiator. A squirrel cage fan is in the plenum and the fan motor extends forward into the rear cavity of the front bumper. A flexible hose connects the air plenum with the motor inlet.

7.4 Controller Installation

The controller is installed above the transaxle on the right side of the vehicle against the firewall. Part of the front traction battery support frame extends back to support the controller and also the on-board charger.

This position allows almost all connections to the controller to be short and direct. Motor leads extend directly below the controller so that the high current leads are very short. Motor and transaxle speed pickup, gear selector, instrument panel and transaxle solenoid leads are all relatively short runs to the controller.

The three-section module of the controller can be removed as a unit or any segment separately for maintenance or modifications.

During shift tuning it was necessary to change microprocessor chips frequently. This can be accomplished in under five minutes by removing only the logic module. Connections to the motor and accessories do not have to be removed.

8.0 VEHICLE TESTING

8.1 Dynamometer Testing

Preliminary testing of the system in the vehicle to refine the controller operation of the armature to field crossover and shift sequencing were done on a roll dynamometer. The dynamometer can be adjusted to provide a wide range of inertia and load configurations. Initially no load was imposed on the system and only a very small inertia, equivalent to a 1500 lb vehicle, so that poor synchronizing would not impose damaging loads on the drivetrain.

Initial attempts to perform shifts on the roll dynamometer were very frustrating. Assumptions made about clutch application and release times were in considerable error. The transaxle was removed from the vehicle and pressure transducers added to measure times to engage and release the clutches. Times to engage varied from one half to two seconds and release times from 200 to 500 mSec. Each clutch has a different engage and release time, fortunately they are reasonably consistent which allows programming the times into the microprocessor to perform the shifts. Figure 8.1-1 shows engage and release times for each clutch.

Once reasonable estimates of shift times were available it was possible to accomplish shifting on the dynamometer, but since the wheels tend to slip on the steel rolls it is not a true indicator of how the shift will be when driving.

Dynamometer testing also allowed tuning of the armature-field transition to eliminate any torque transient. This is accomplished by inserting logic time delays equal to the transition time of the crossover contactor

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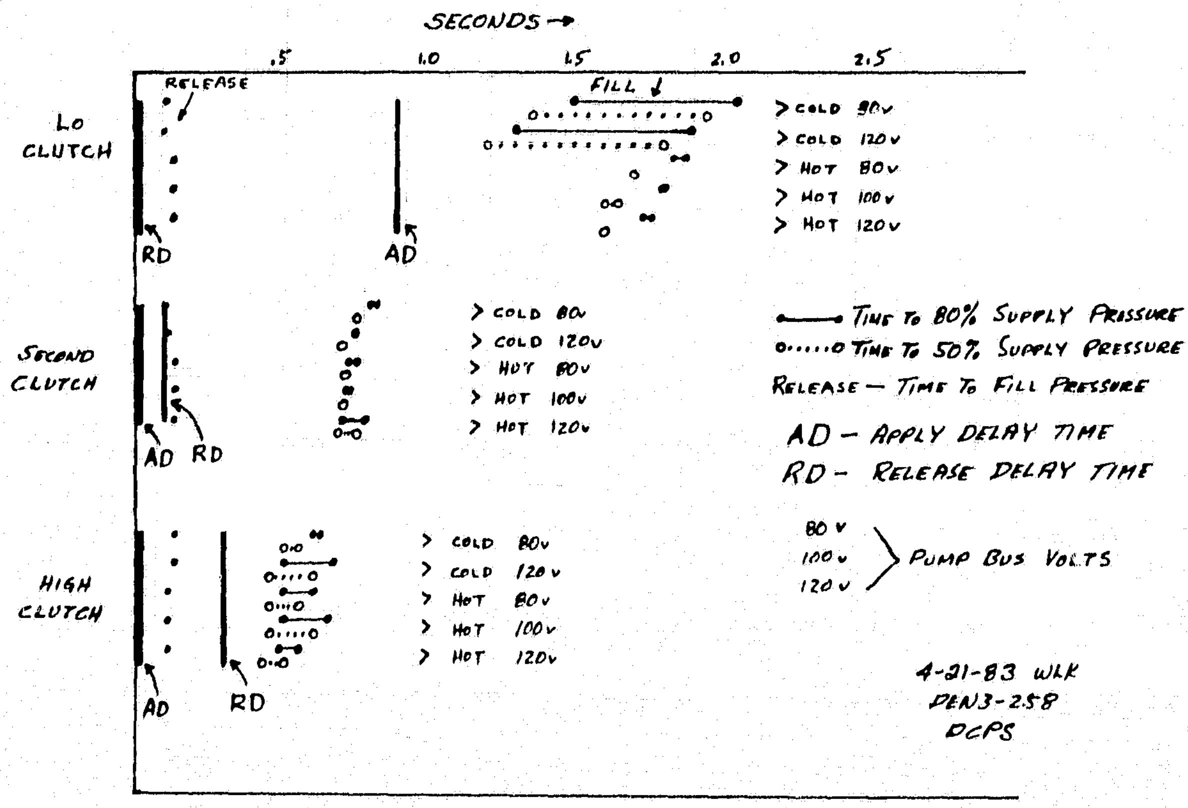

Clutch Response Times
3-speed Transaxle

Figure 8.1-1

used for switching from armature to field control. Time for the contactor to pull in is much shorter than to drop out, which requires an asymmetrical delay.

8.2 On-the-Road Shift Tuning

As expected, the shifts were different without the wheel slip experienced on the dynamometer. Considerable time was required to determine the optimum time delays for clutches to release and engage.

A typical shift sequence, from first to second gear, consists of first releasing the first gear clutch, waiting the release delay time, applying the second gear clutch, waiting the apply delay time, syncronizing the motor by applying a downspeed command causing maximum regeneration. If all times are correct, a reasonably smooth transition results. Each upshift and each downshift requires separate timing for each phase of the shift. Figure 8.2-1 shows the timing sequences and delays for performing each shift, up or down.

8.3 Track Testing

8.3.1 Test Plan

The testing was performed according to the plan submitted and approved by the project cordinator at NASA. The test plan was published as Technical Report No. 83009.

8.3.2 Instrumentation Procedures

Instrumentation for the DC vehicle testing was reduced to the minimum based on experience with the AC system. With the mobile test lab on location to reduce the data immediately following the test, it was not necessary to use the chart recorder and gasoline powered generator.

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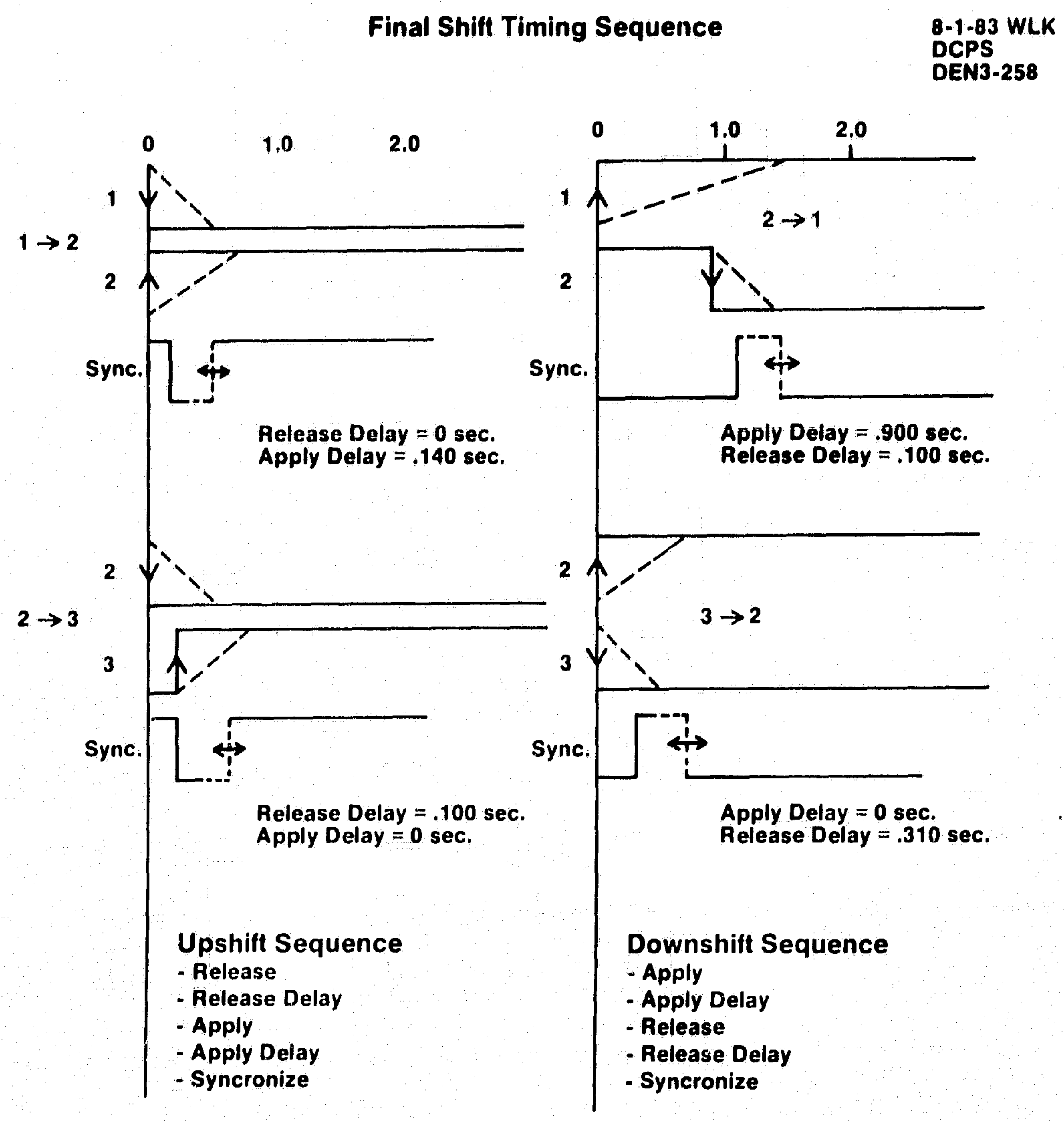

Figure 8.2-1

Instrumentation consisted of

. fifth wheel,

. bus voltage attenuator-isolator,

. bus current sensor-isolator,

. 4-channel FM recorder (one channel for drift compensation) and

. 12v to 115 vac inverter to power bus voltage and current amplifiers.

See Figure 8.3.2-1.

From this instrumentation, the following data was recorded:

. vehicle speed with respect to time,

. bus volts with respect to time and

. bus current with respect to time.

Before running a test sequence, the zero and calibration of each instrument were checked. These reference values were then recorded for later reduction of data on the computer. At the end of a test sequence the zero and calibration were again checked to make sure no drift occurred during tests.

After a test sequence was completed, the tape was played into the mobile lab's computer and transferred to disk storage for future data reduction. It was customary to sample the data from each test to confirm results before going on to the next test sequence. If any data were suspicious or not suitable, the test could be repeated as soon as the vehicle's batteries were recharged.

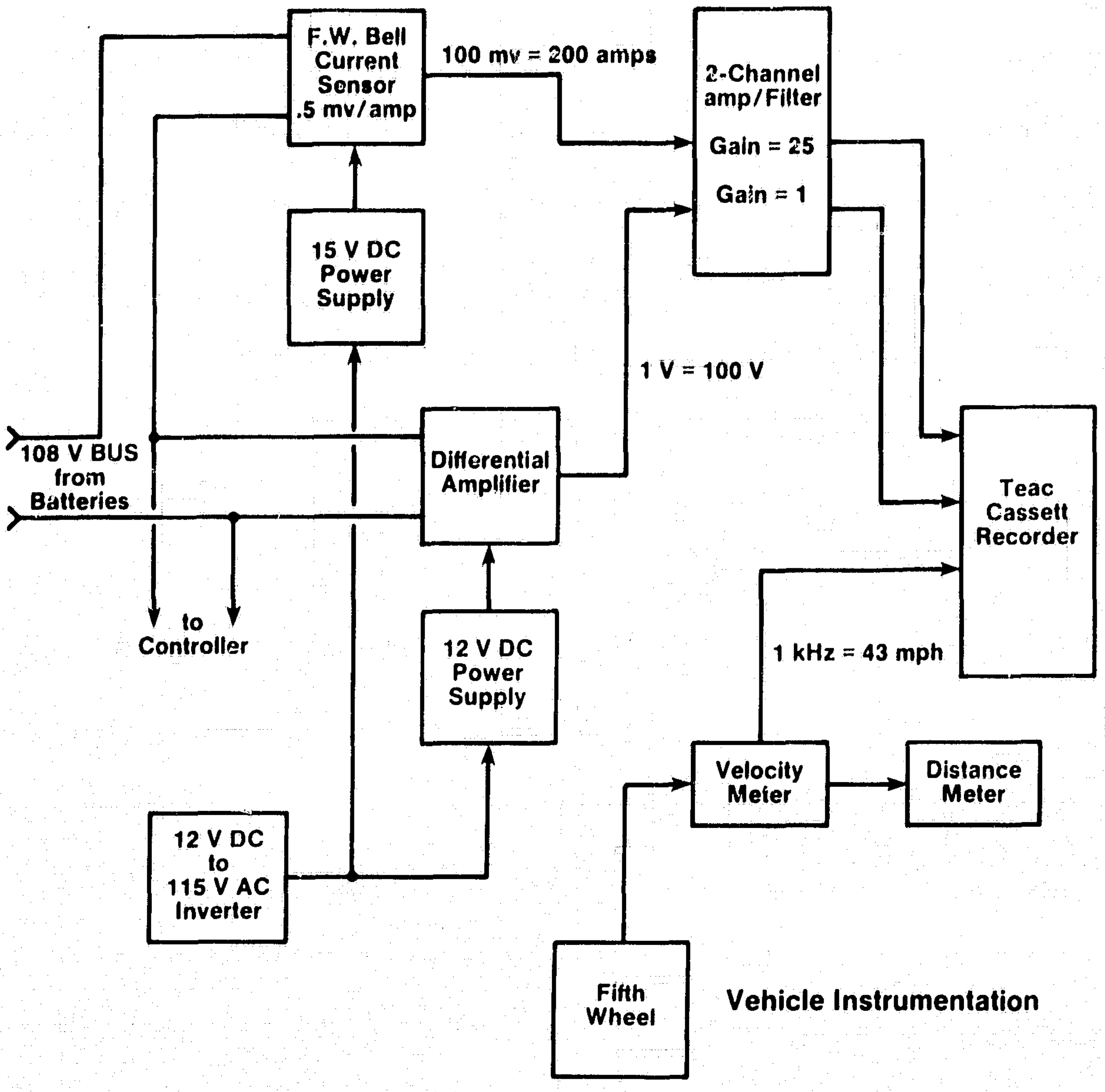
F.W. Bell Current Sensor .5 mv/amp
100 mv = 200 amps
2-Channel amp/Filter
Gain = 25
Gain = 1
15 V DC Power Supply
1 V = 100 V
108 V BUS from Batteries
Differential Amplifier
Teac Cassett Recorder
to Controller
12 V DC Power Supply
1 kHz = 43 mph
Velocity Meter
Distance Meter
12 V DC to 115 V AC Inverter
Fifth Wheel
Vehicle Instrumentation

Figure 8.3.2-1

8.3.3 Test Results

The first tests run were the constant speed energy consumption. The computer reduced test data to show:

- . battery power (watts) with respect to time,
- . battery expend energy (joules) with respect to time,
- . test distance with respect to time and
- . watt-hours per mile with respect to time.

Figure 8.3.3-1 shows a typical set of recorded data, and Figure 8.3.3-2 shows the reduced data.

By observing the data on the terminal, a segment of a test could be selected where speed and power were constant. A period of several seconds would be used to determine the average values of bus current, voltage and vehicle speed.

Each sequence of testing was recorded and reduced to give an average of several test runs.

A typical test run for maximum acceleration is shown in Figure 8.3.3-3.

A typical SAE J-227a/D cycle test is shown in Figures 8.3.3-4A and B. To achieve results as accurate as possible, the test was run following a profilometer that displayed desired vehicle speed beside actual speed. At the end of each cycle is an "idle" period. This time is included in the result since power is being consumed by the logic and the hydraulic pump, even if the vehicle is not moving.

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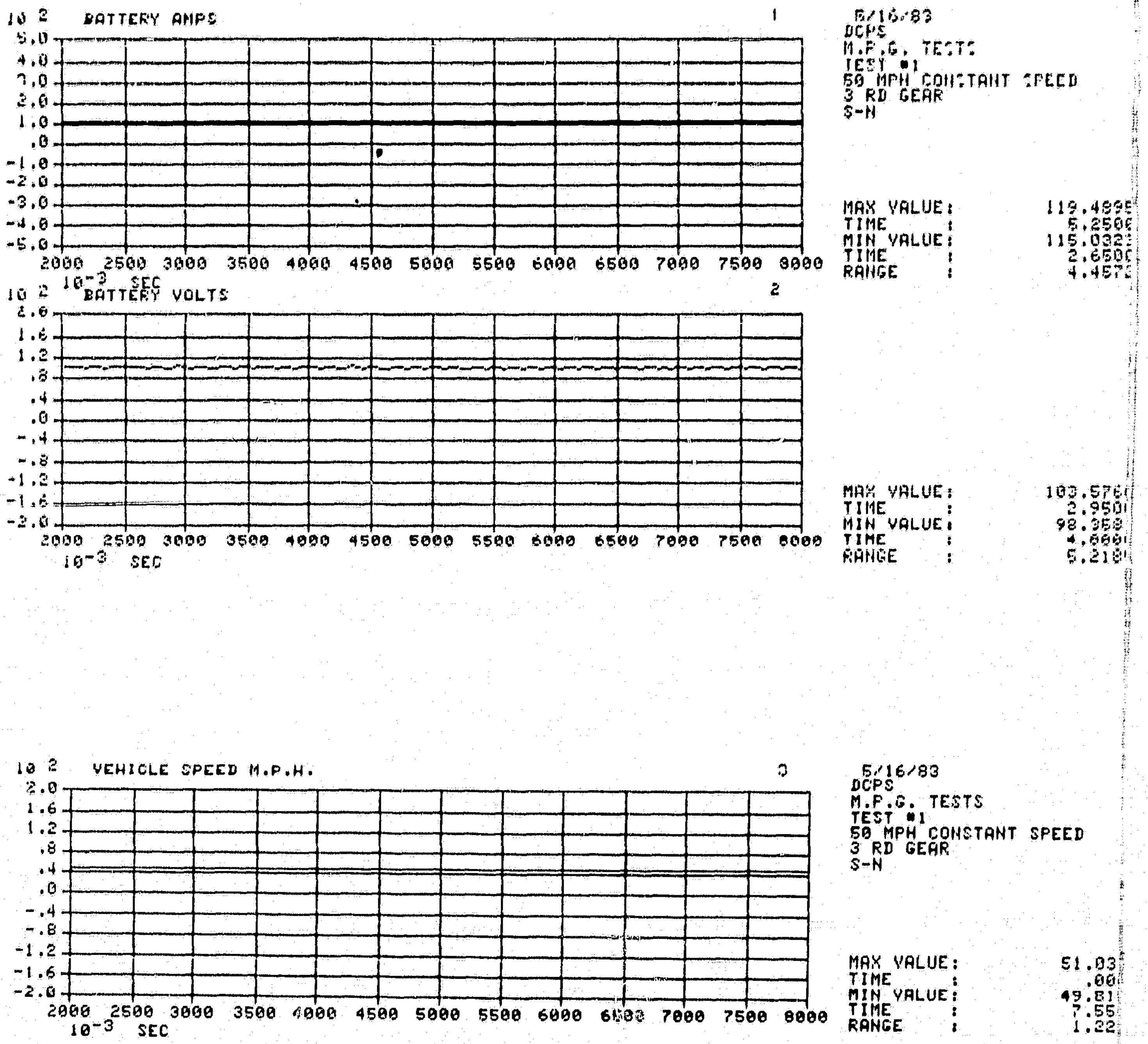

Typical Data From Constant Speed Test,
Current, Voltage and Speed Versus Time

Figure 8.3.3-1

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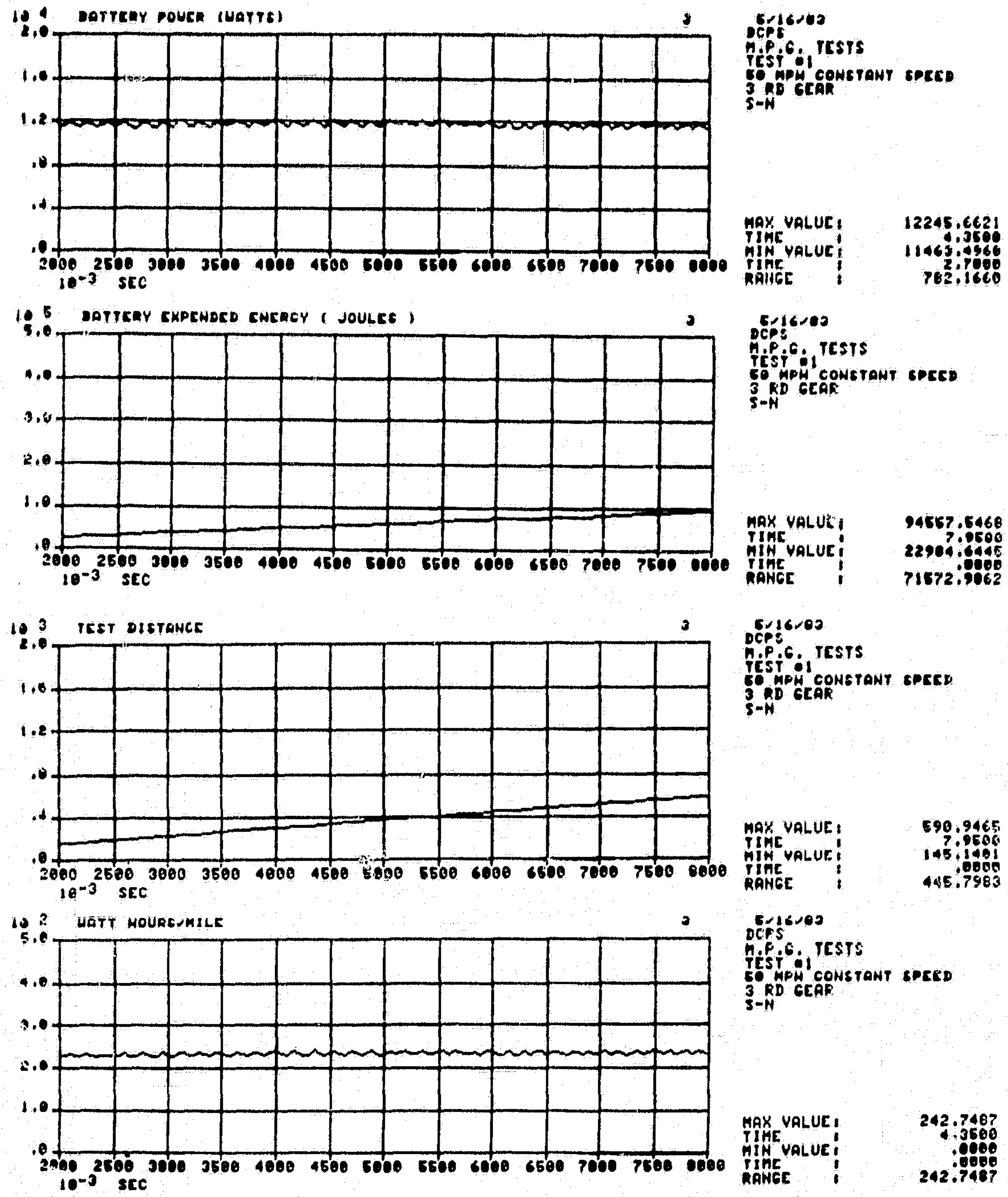

Computer Reduced Data from Constant Speed
Test, Power, Energy, Distance and
Watt Hours/Mile

Figure 8.3.3-2

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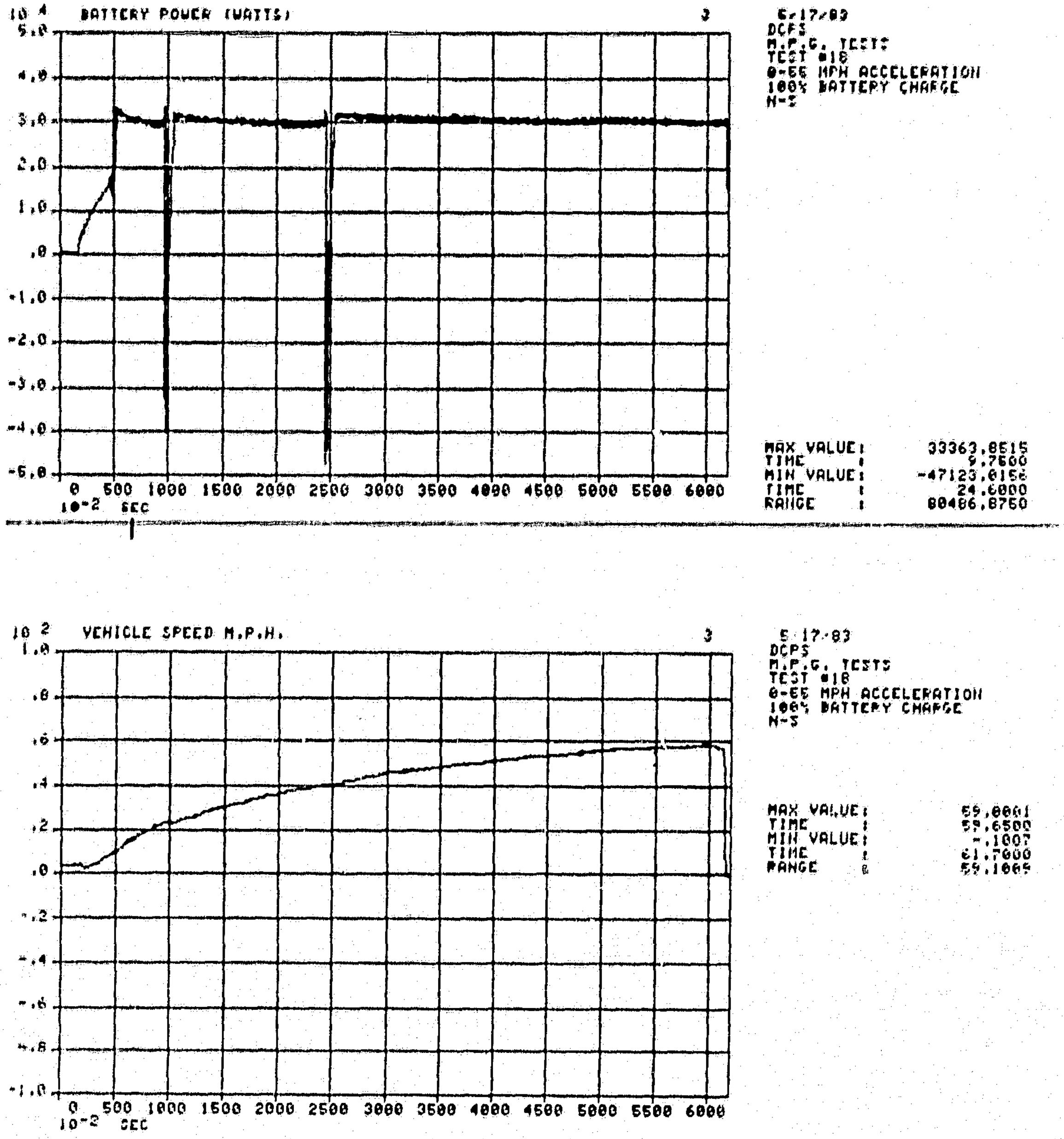

Reduced Data from An Acceleration Test, Power and Speed Versus Time

Figure 8.3.3-3

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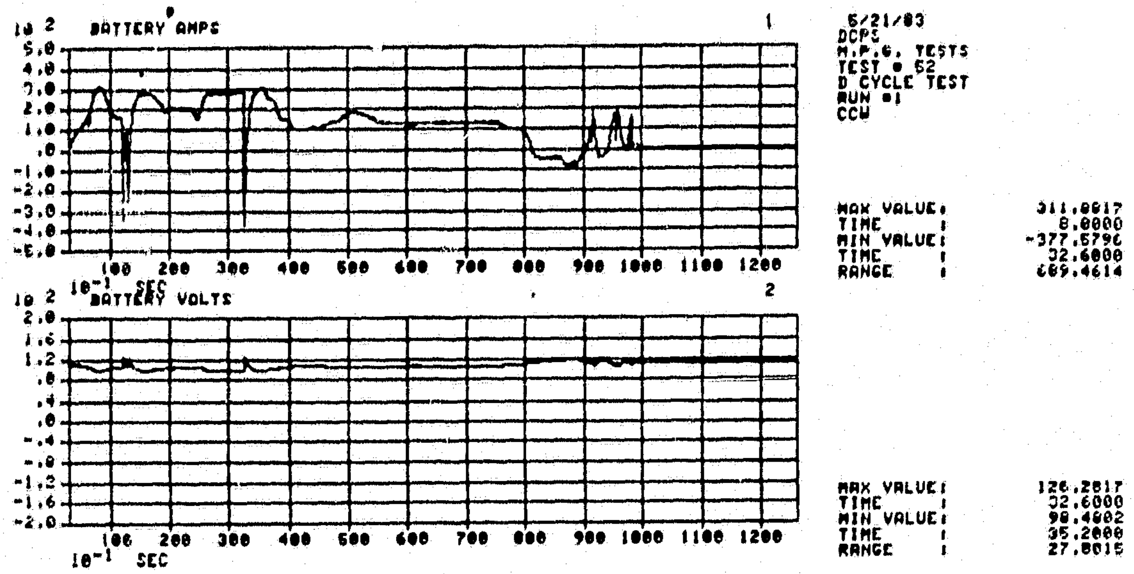
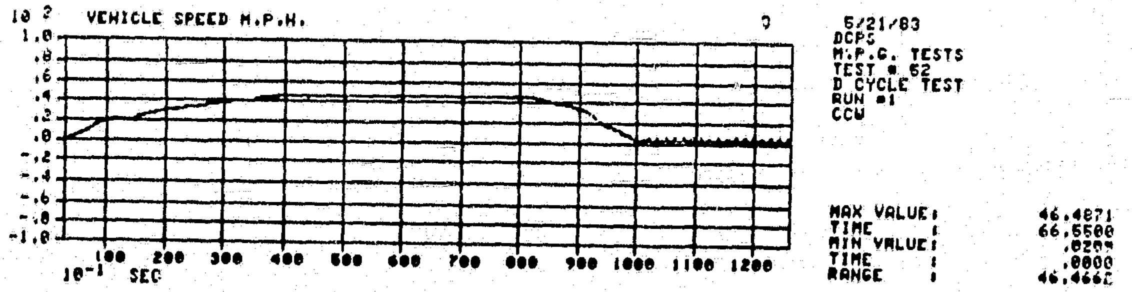
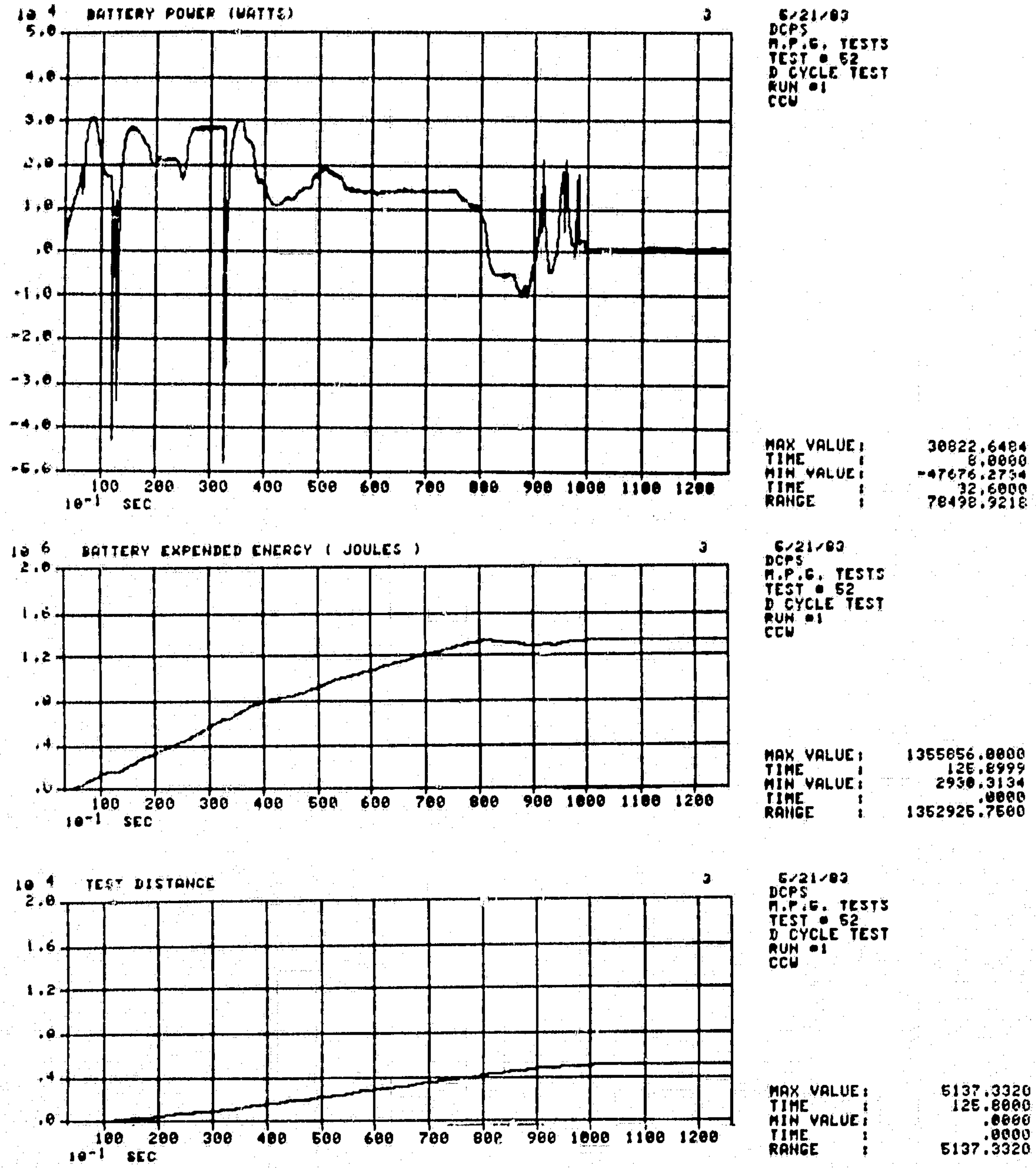




Data From a Typical SAE J227A/D Test, Current, Voltage and Vehicle Speed Versus time

Figure 8.3.3-4A Measured Data



Reduced Data from SAE J227A/D Test, Power, Energy and Distance

Figure 8.3.3-4B

Watt hours per mile is derived from energy (joules) divided by test distance, 5137 ft., and is 386.3 wh/mi.

A high-speed run was conducted to confirm the vehicle could achieve at least 65 mph. Two laps of the track covered 3.2 miles at an average speed of 62 mph. During this run, speed varied from 60.5 to 67.8 mph. At one point, as seen in the data, the vehicle was allowed to slow somewhat to prevent having to enter a banked turn above 65 mph. Figure 8.3.3-5 shows speed and power during this run.

The braking tests were conducted to confirm the vehicle was capable of decelerating at an acceptable rate. During the tests, the vehicle tires were not at the point of sliding, and a higher rate could be attained if necessary. At no time during the tests did any vehicle instability become apparent that would prevent stopping at high rates of deceleration.

It should be stated that the braking effort required for such a small vehicle is excessive. To achieve 15 ft/sec^2 rates of deceleration, pedal pressures exceeding 160 lbs. can be necessary. This is quite high for any person of small stature. To cause wheel lockup, pressures considerably higher are necessary.

Figure 8.3.3-6 shows braking pedal pressure and a vehicle speed profile. A rate of 14.67 ft/sec^2 was sustained during this test.

The test was performed using a U-tube accelerometer attached to the windshield to observe deceleration rate while braking.

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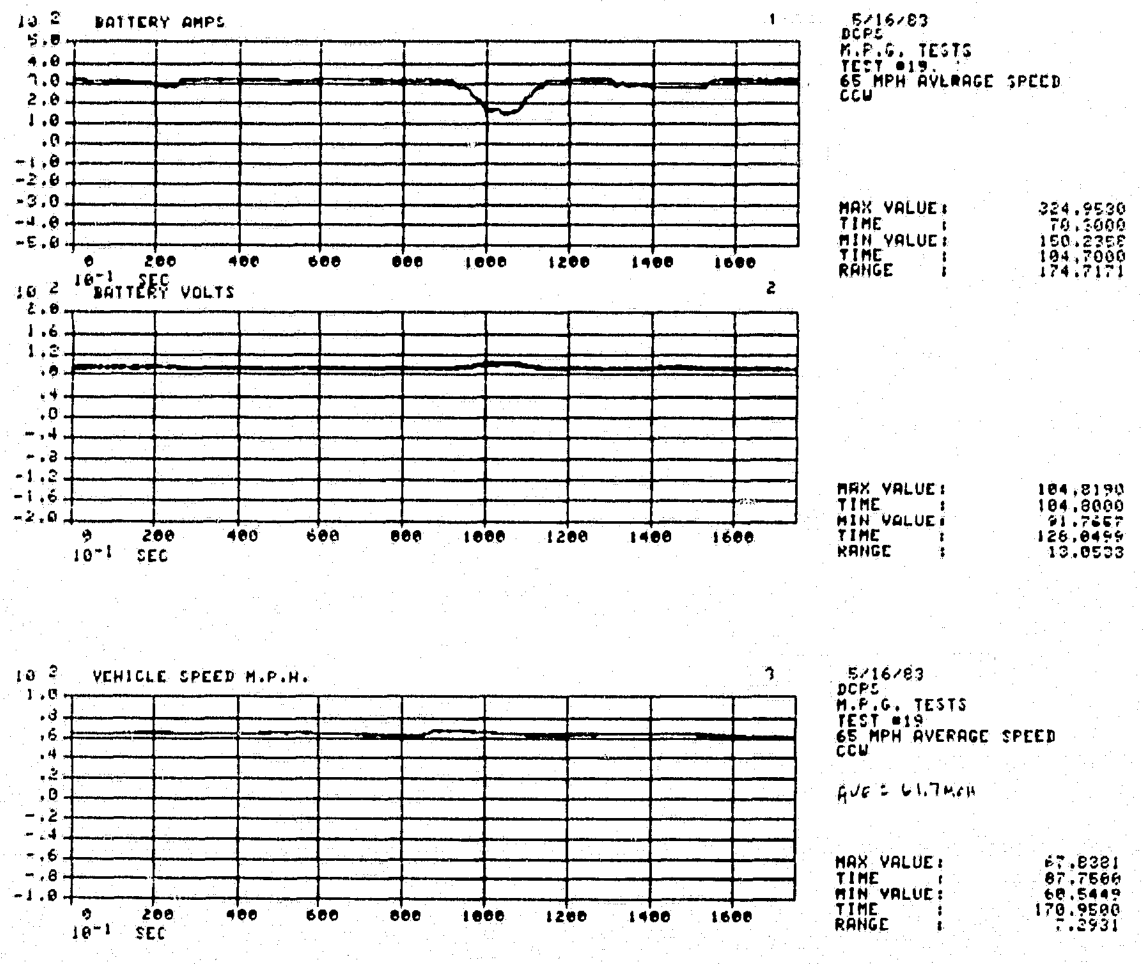

Data from a High Speed Test Run, Current, Voltage and Vehicle Speed Versus Time

Figure 8.3.3-5

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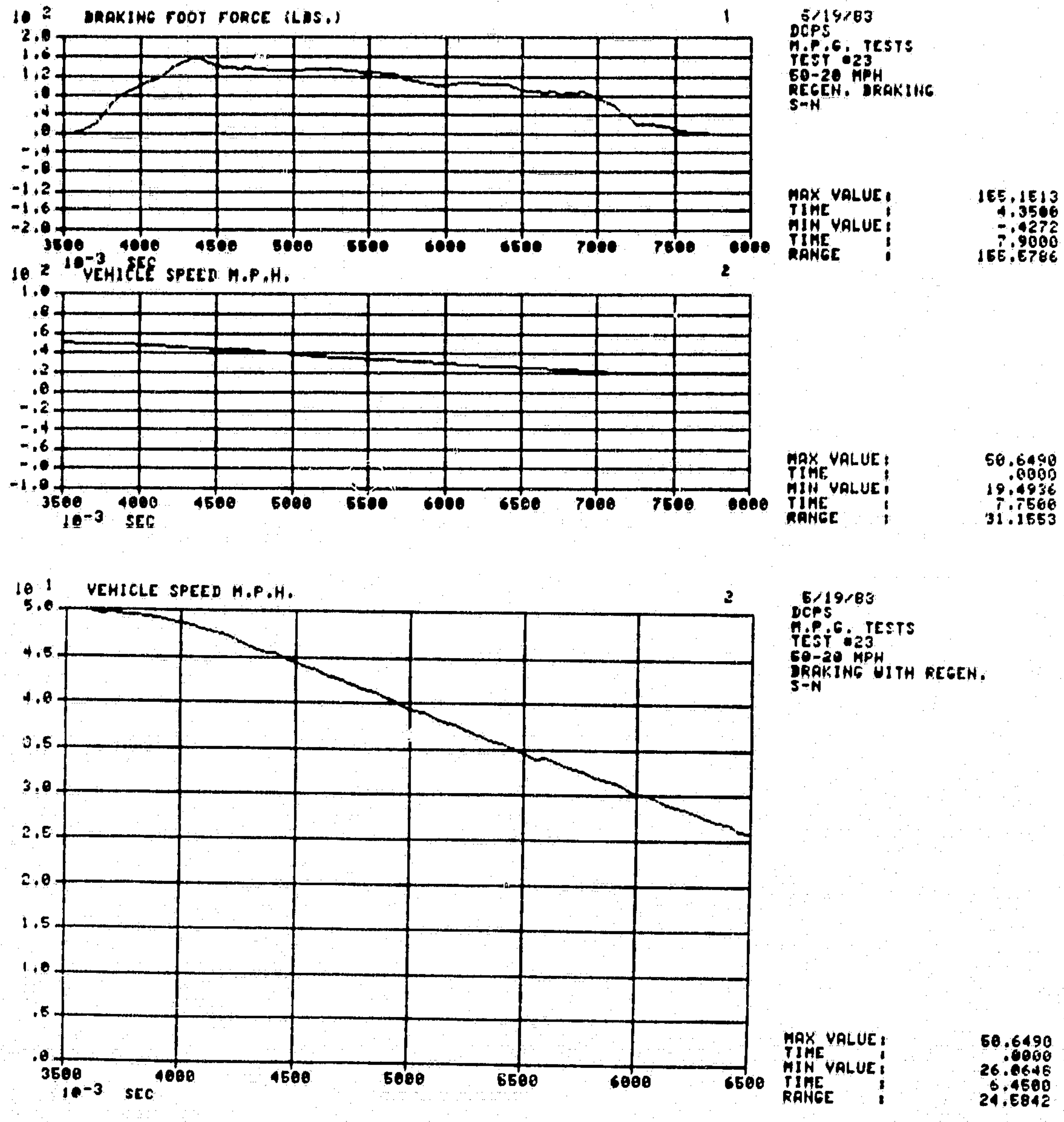

Data from Braking Test, Pedal Pressure and
Vehicle Speed Versus Time

Figure 8.3.3-6

Pedal pressure was modulated in order to maintain and approximate 15 ft/sec^2 rate of deceleration.

One test originally planned, the regeneration test, could not be performed. Because the downshift sequencing was not set to the proper vehicle speeds, the vehicle would decelerate to a speed just above the downshift point, and the brakes had to be applied to force the speed down to permit a downshift. This became apparent just prior to track testing when the traction motor warmed up during street testing. While cold, the base speed of the motor was low enough that the downshift would occur without using the brakes. As soon as the field of the motor warmed up, the base speed rose slightly and only by braking would the vehicle slow to the downshift setpoint speed. Because of time and cost limitations, it was not considered worthwhile to reprogram the microprocessor control for this one test.

The final test performed was the coastdown test. The objective was to establish the actual vehicle aerodynamic and rolling drag coefficients. For this test, the axle shafts were disconnected and the vehicle towed to a speed above 50 mph and released. The speed was recorded as a function of time. The test was run in opposite directions to eliminate wind and grade effects.

Figure 8.3.3-7 shows a typical test run with speed versus time. This data was then reduced on the computer to obtain a best fit answer matching the coastdown profile to an equation for air and wheel drag.

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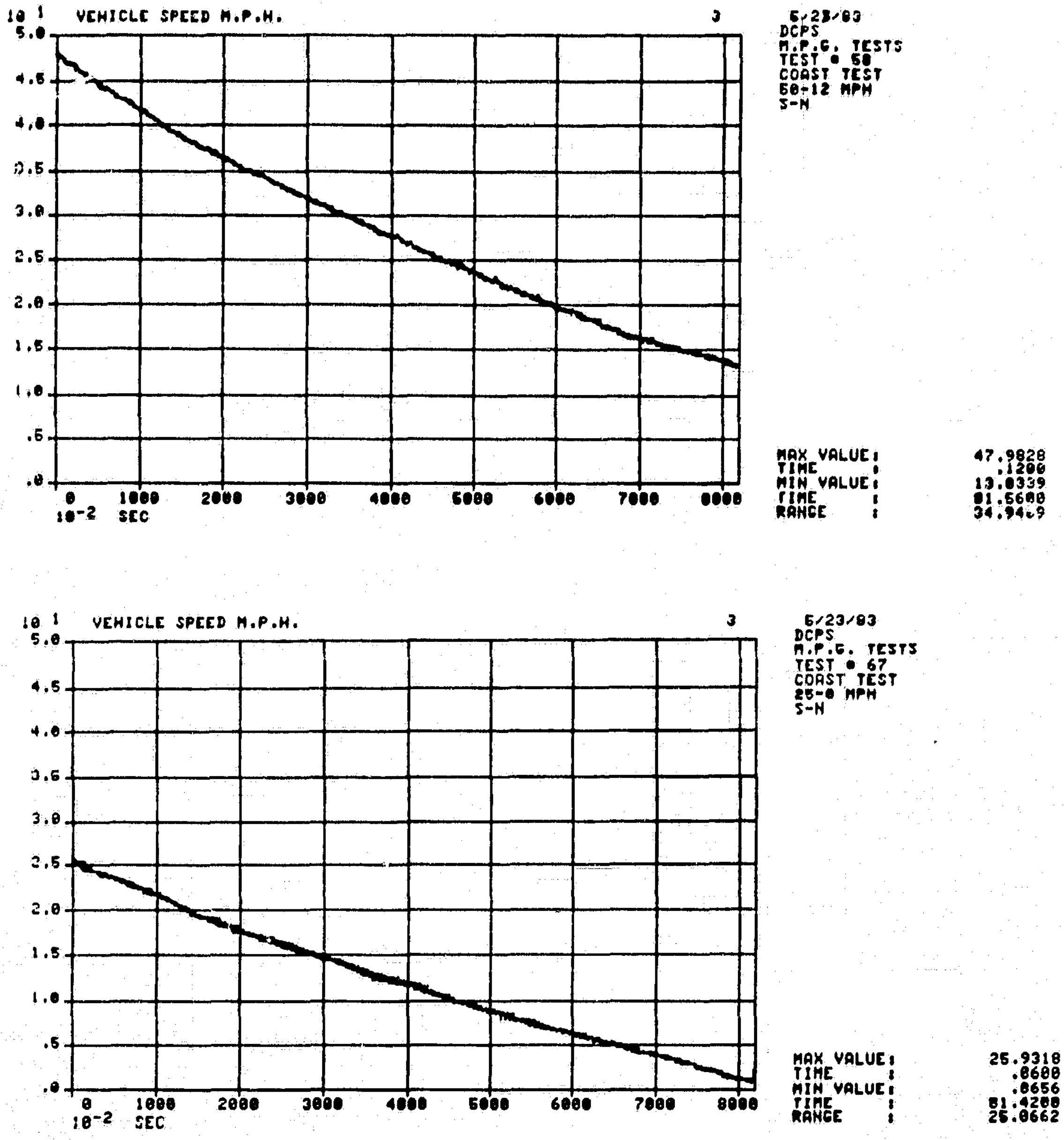

Coast Down Speed Versus Time

Figure 8.3.3-7

Since the coastdown distance exceeds the available straight line distance available, the data was recorded in two segments and combined for reduction by the computer.

FINAL RESULTS OF COASTDOWN TEST

The results compare favorably to the original calculated values and the final results from the energy consumption tests.

Since both the ac and dc vehicles have the same aerodynamics and weight as tested, a comparison of coastdown results are given below:

	AC (Weight = 3640) (50 deg F. ambient)		DC (weight = 3620) (68 deg. F. ambient)	
Speed	Road Load	C/dA	Road Load	C/dA
0	47.5		48.5	
25	61.7	.467	62.1	.448
50	104.3		102.9	
	Drawbar Test at zero speed = 57 lbs (40 deg. F. ambient)		Drawbar Test at zero speed = 52 lbs (68 deg. F. ambient)	

8.4 Comparison with AC2 Propulsion System

Because both programs used identical base vehicles, it is an obvious choice for comparison. The AC vehicle results were adjusted for weight and drag and compared very well to the ETV-1 vehicle. No adjustments are necessary to compare the AC to the DC system for energy consumption.

Table 5 shows energy consumption in watt hours per mile for both vehicles as a function of speed.

Table 5

Speed	AC2	DC
15	N/A	240 wh/mi
20	N/A	227
25	214	203
35	225	226
45	226	246
50	300	266
55	N/A	299
D cycle	355	374.5 no regeneration
	320	N/A w/regeneration

Data from these tests are shown in the bar graph in Figure 8.4-1.

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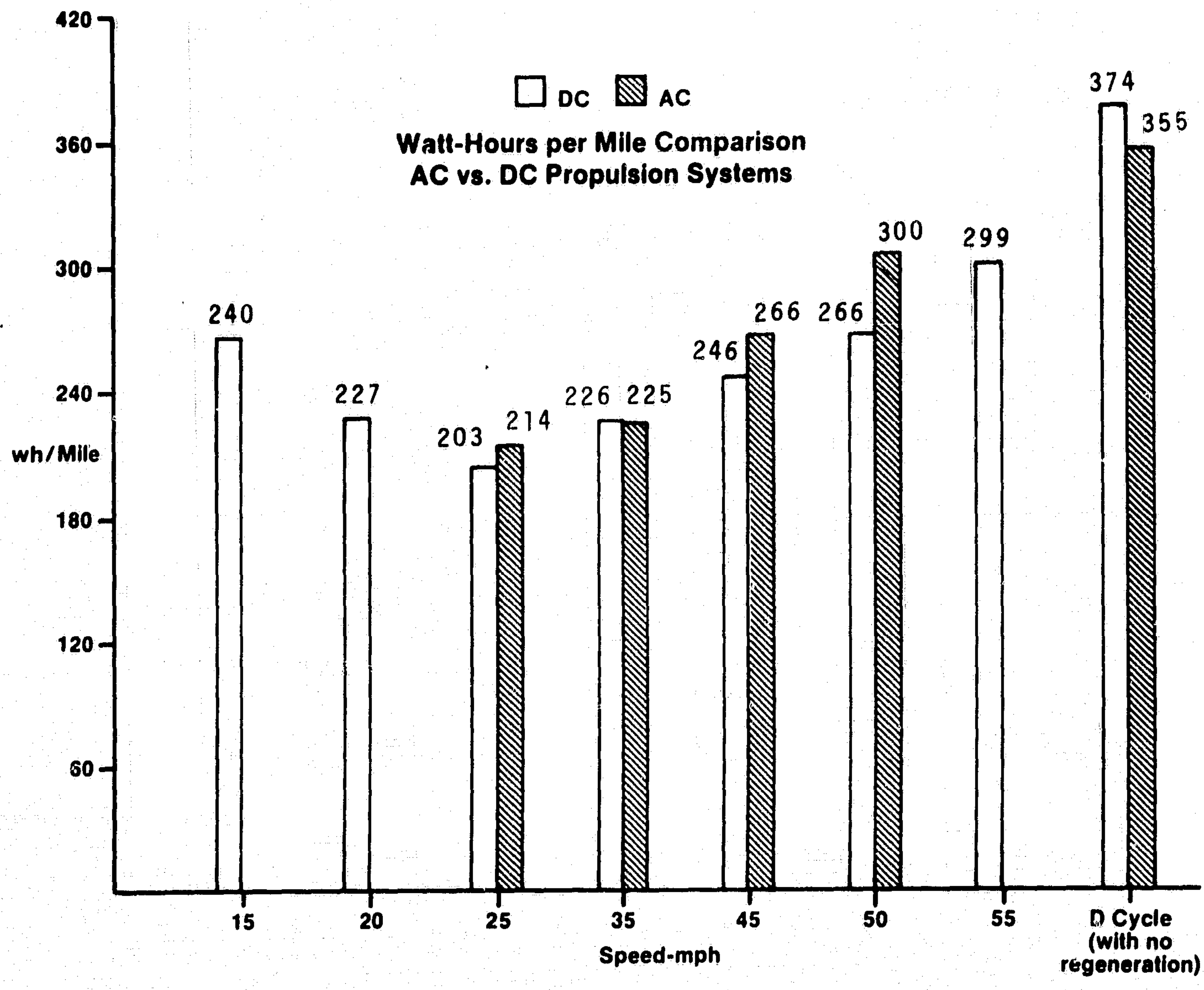

Figure 8.4-1

The final results have been compared to the predicted to verify the accuracy and assumptions made about vehicle dynamics. One change was made to improve efficiency and shift quality. The shift points were originally to be at 17 and 31 mph; this was changed to 23 and 41 mph. This change keeps the traction motor in a more efficient operating condition while cruising at steady speeds, generally lightly loaded in the weak field condition.

Figure 6.3.1-1A shows a revised system efficiency prediction graph based on these shift points.

Figure 8.4-2 shows a comparison of predicted versus measured watt-hours per mile based on these shift points. In most cases, measured power consumption is less than predicted, indicating test data on components was interpreted conservatively.

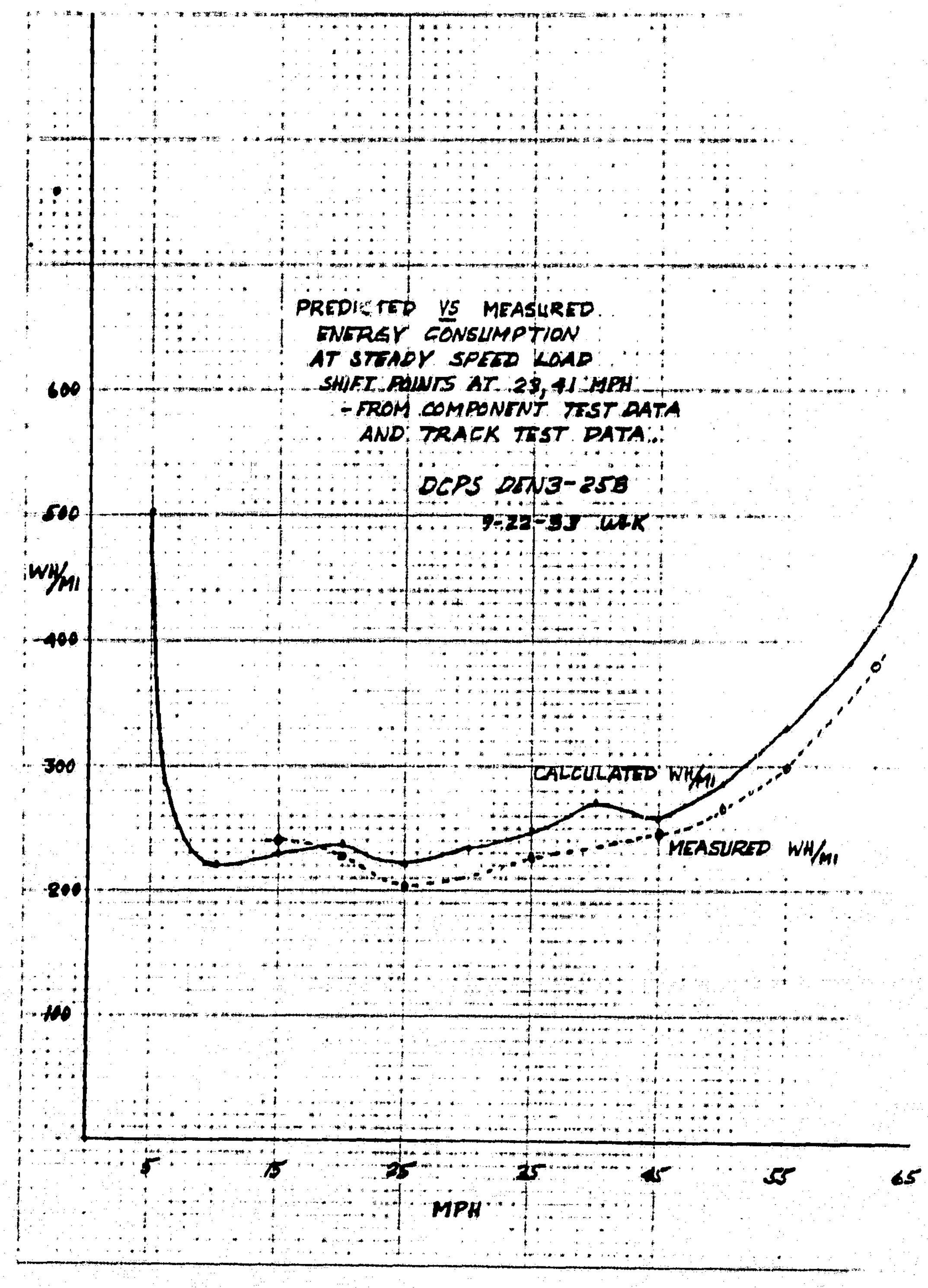
PREDICTED VS MEASURED
ENERGY CONSUMPTION
AT STEADY SPEED LOAD
SHIFT POINTS AT 23, 41 MPH
- FROM COMPONENT TEST DATA
AND TRACK TEST DATA.
DCPS DEN3-25B
9-22-83 WGK
600
500
WH/MI
400
300
200
100
CALCULATED WH/MI
MEASURED WH/MI
5
15
25
35
45
55
65
MPH

Figure 8.4-2

9.0 DC PROPULSION SYSTEM PRELIMINARY COST ANALYSIS

These cost figures are Research Center engineering estimates based on the previous cost analysis performed for the AC Phase-One Program.

Estimate of EV Propulsion System OEM Costs
Four-Passenger Vehicle - 1980 Dollars

Component	Quantity 10K	Quantity 100K
Motor	1340	780
Transaxle	875	510
Power Converter	150	125
Logic Controller, Contactors and Sensors	375	225
Total	2740	1640

10.0 CONCLUSIONS

1. The Eaton automatically-shifted mechanical transaxle can be effectively integrated into a near-term electric vehicle DC powertrain.

2. When coupled with a field weakening type DC motor, the transaxle should have three forward speeds.

3. The three-speed transaxle design has satisfactorily met all design objectives: structural soundness, heat dissipation capacity, efficiency, freedom from excessive noise and vibrations, function of the parking latch mechanism, and adequate lubrication and cooling of all components appear to be satisfactory based on observations of completed dynamometer and proving ground tests.

4. Shift duration and consistency, while satisfactory, appear as those areas where further improvement would add to the attractiveness of the three-speed transaxle as a product.

5. A separately excited, field weakening traction motor is a totally satisfactory approach to DC traction. The motor is efficient, easy to control and easily regenerates when above base speed.

6. A limited current range armature chopper/field chopper combination controller makes an attractive approach for a DC vehicle with a multispeed transmission.

7. The combined efficiencies of the motor-controller-transaxle rival the Phase 2 ac system under steady speed load conditions. DC system efficiency drops significantly, however, during hard acceleration due to the motor characteristics being optimized for cruising efficiency, whereas the AC system tends to hold its efficiency.

8. The individual components of the system are produceable with today's technology without delays being required for further development in semiconductor device.